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The Annual Reference Index to ELECTRICAL ENGINEERING for 1933 Is Now Available

Fundamental Properties of the Electron

By ALAN T. WATERMAN
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New Haven, Conn.

THE ATOMIC NATURE of electricity, the realization that an electric charge or current consists of minute electrons, may be considered to be the second vindication of the atomist school of Greek philosophy which so earnestly and ably argued against the continuity of matter or its infinite divisibility. Although ordinary matter already had been shown to consist of atoms and molecules, the physicists of the eighteenth and the early nineteenth centuries had come to regard electricity as a continuous fluid and possibly not like matter at all in the ordinary sense. This conception lent itself readily to theoretical development, even to the extent of explaining in the expert hands of Maxwell the nature of light as electromagnetic wave motion. The picture of the ultimate nature of electricity, however, remained vague in spite of this progress. The first evidence as to its atomic nature was implicit in the laws of electrolysis discovered by Faraday in 1834, although Faraday seems not to have stressed this conclusion. Maxwell himself refers to the possibility, but it remained for Stoney in 1874 to make use of this hypothetical particle which he christened the "electron."

Presenting clearly and concisely a story of the evolution of the electron, as seen from the viewpoint of modern theoretical physics, this article reveals that the electron in many respects is following the "trend of the times." A review of the status of the electron reveals clearly that its properties have been extended well beyond those contemplated by its discoverer; also that, in following the simple and apparently necessary expedient of endowing the electron with such properties as a wave aspect and a change of mass with velocity, the vividness of the mental conception of an electron has been dulled. The author indicates that, in addition to the mental picture of fundamental atomic processes having become more difficult or even impossible, the intrinsic precision of the processes themselves is called into question by the most recent theories. This is the second in a series of special articles developed under the sponsorship of the A.I.E.E. committee on education.—Editor

The laws of electrolysis become almost self-evident if a definite electrical charge, or some multiple thereof, is carried by atoms in electrolytic solution. What then is more natural than to assume the existence of a universal particle of electricity? The size of this charge evidently is the total charge passed through the solution, divided by the number of carriers. Unfortunately, although the charge transported may be measured easily, the number of carriers is more difficult to ascertain. However, the mass of substance liberated along with the electricity is measurable; it should be equal to the desired number multiplied by the mass of each. Thus, simple observations of the mass of substance M and the total electrical charge E liberated at a given electrode, since each involves the same number of particles, yield at once by their quotient E/M the ratio e/m of the charge on *each* particle to its mass. (Strictly speaking, of course, only the average value is obtained.) The stage then is all set for progress in two directions: an independent determination of m will determine e, and *vice versa*. Thus, in an experiment that may be performed quickly by an elementary student, we find ourselves on the road toward knowledge both of the atom and of electricity.

Electric Discharges in Gases

The next step in the isolation of the electron came from the study of electrical discharges in gases. At low pressures mysterious rays were seen to proceed, apparently from the cathode, hence called "cathode rays." Traveling as they did, away from the negative terminal, these rays, if particles, should bear a negative charge. It was necessary however to prove that they were not some form of ray like light, and this was difficult because of their straight paths and the fluorescent effects they caused, as well as from the obvious light effects present during the discharge at higher pressures. That they were electrified became evident when they were found to be deflected by a magnetic field, precisely as the armature of a simple electric motor is propelled by the magnetic influence of the field magnet (for electricity in motion should constitute an electric current and be subject to the same laws). The direction of their deflection and also their deviation by an electrostatic field, in conjunction with their source, confirmed their electric charge as negative. From their mechanical and heating effects upon impact they were seen to possess mass. Assuming by analogy with electrolysis, therefore, that the cathode rays were negatively charged particles of definite mass and velocity, Schuster found in 1870 that the velocity and the charge-to-mass ratio e/m could be determined from the amount of deflection in electrostatic and magnetic fields. This ratio turned out to be about 1,850 times as large as the corresponding value for the hydrogen ion in electrolysis. Evidently either the charge on each particle would have to be enormously greater than ionic charges in electrolysis, or the mass of the particle should be correspondingly smaller; perhaps both.

Sir J. J. Thomson in a series of masterly studies of the conduction of electricity through gases beginning in 1895, showed that, although the speeds of the cathode rays depended to a certain extent upon the conditions of the experiment, the value of the charge-to-mass ratio was the same regardless of the kind of (rarefied) gas used in the tube and regardless of the material of the electrodes. The presumption, therefore, was that the cathode rays were streams of new *universal* negatively charged particles. Upon making the reasonable assumption that the charge carried by each cathode particle was equal to the elementary unit-charge involved in electrolysis, the mass of each particle should be about $^1/_{1,850}$ of the mass of the lightest known atom, hydrogen. In this way the existence of Stoney's "electrons" seemed to be demonstrated. Incidentally, the mass of this electron was so small that the difference in weight of a positively and a negatively charged body would escape detection.

CHARGE AND MASS OF AN ELECTRON

It remained for Millikan, between the years 1908 and 1917, by perfecting a method originated by Townsend in 1897 and improved by J. J. Thomson and H. A. Wilson at Cambridge, to measure to an accuracy of 1 part in 1,000 the electrical charge ($e = 1.59 \times 10^{-19}$ coulombs) carried by a single electron. From the known value of e/m its mass could then be found in *grams*, this proving to be 9×10^{-28} grams. At once the mass of every atom was known in terms of ordinary units, instead of merely with reference to that of oxygen as in the chemical atomic weights. Off hand, the measurement of any quantity as small as the electronic charge would seem to be out of the question. In principle, Millikan's method consists essentially in the use of a strong electric field to support a minute electrically charged oil drop in the space between 2 condenser plates where it may be observed through a microscope. The force on a charge q in a field E is Eq and, if the particle is to remain suspended, this force must equal its weight w. Hence, in equilibrium, $Eq = w$ and q is computed by a knowledge of E and w. The ingenuity of the device consisted in applying an electric field large enough to make up for the smallness of the charge and thus produce a force sufficient to equal the weight of the drop, which weight could be determined in several ways. In practice it was found expedient not to hold the drop stationary, but to measure its upward and its downward drift with the field on and off, respectively. The charge on the drop was obtained by allowing it to pick up ions from the air, which was ionized by exposing it to X rays or to a radioactive source. It was found that practically all drops bore the same charge no matter what the gas, its ionizing agent, or the size or nature of the drop; none carried less than this charge; a few carried exactly twice as much or, rarely, exactly 3 or 4 times as much. The electron thus was established as a particle of definite mass and electric charge; presumably it was the fundamental unit in electrical phenomena.

CHANGE OF ELECTRONIC MASS WITH VELOCITY

Paralleling this advance there came, from the then new field of radioactivity in the study of the β rays isolated by Rutherford, evidence of the new particles as an integral constituent of the atom. In 1902 Kaufmann, by deflection methods similar to those used for cathode rays, determined the value of e/m for β rays. Their speeds proved to be much higher than those of cathode rays, approaching in some cases the speed of light (186,000 miles per second). For all except the fastest β rays the value of e/m agreed with that for cathode rays, and the β rays thus were identified as electrons. For the case of an electron, the fastest rays proceeded to furnish a striking verification of a proposal made by Lorentz that mass might be electromagnetic in nature; a proposal later generalized by the theory of relativity to the effect that mass and energy are equivalent and connected by the relation (in CGS units): $mass = energy/c^2$, where c is the velocity of light in a vacuum. Lorentz first showed that by virtue of its charge alone an electron would have to possess inertia, and hence mass, even if not endowed with mass as ordinarily conceived. That this is true may be understood from the fact that when an electron is accelerated its surrounding magnetic field caused by its motion is increased. Now, a magnetic field represents energy; to increase this field requires the expenditure of energy; consequently a force is required to accelerate the electron *because of its electrical charge alone;* therefore, a pure electrical charge must have the property of mass. For ordinary speeds, and for a charged sphere of radius a and total charge e, this electromagnetic mass is computed to be $2\,e^2/3\,ac^2$. In passing, it is interesting to note that, subject to its verification, this hypothesis makes possible a rough estimate of the dimensions of an electron. If the electron is a charged sphere possessing only electromagnetic mass, its radius would be 1.85×10^{-13} cm, roughly $^1/_{50,000}$ the diameter of an atom. Lorentz and others

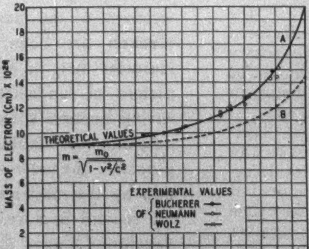

Fig. 1. Variation of electronic mass with velocity. Curve A, theoretical values; Curve B, assuming half the mass invariable

(From "Atomic Physics," Physics Staff, University of Pittsburgh) further showed that the electron's mass (transverse), although constant for ordinary speeds, should increase rapidly as its velocity approached the speed of light, according to the expression $m = m_0/(1 - \beta^2)^{1/2}$ where $\beta = v/c$ the ratio of the speed of the electron to that of light and m_0 is the "rest-mass" of the electron. The same result is obtained more directly and more generally from relativity theory. This matter was put to experimental test by Bucherer, who found by an ingenious application of the deflection method that this law was obeyed closely for fast electrons from radium fluoride. The mass of an electron moving with 98 per cent of the speed of light, for instance, proved to be more than 5 times its rest-mass, although the difference is not detectable for speeds less than $^1/_{10}$ that of light.

THERMIONIC AND PHOTOELECTRIC EMISSION; THE QUANTUM THEORY

Along with the investigation of the electron, and contributing to its establishment, came an investigation the application of which was destined to be of the greatest importance, both commercially and in research. Chiefly as a result of the efforts of O. W. Richardson and his coworkers for a period of years beginning about 1900, the phenomenon of thermionic emission was analyzed and its laws discovered. Substances, especially metals, when heated were observed to emit electricity which proved to consist of these same electrons. A quite satisfactory theory of this behavior assumed the electrons to exist within the hot body somewhat as a gas which "evaporated" from the surface when heated. The analogy holds further for, corresponding to the heat of vaporization, the electron has to do work w in order to escape. Very soon Fleming in England saw in this effect the possibility of using a hot and a cold electrode in an evacuated tube to operate as a unidirectional valve, or rectifier, for electric currents. The current, in the form of electrons, will pass only from hot to cold electrode. De Forest added a third electrode in the form of a grid between the others, thus adding flexibility, control, and the possibility of amplification. The subsequent sensational development of the vacuum tube as radio detector, amplifier, oscillator, and for other uses is well known.

In the meantime Max Planck in 1900 had set the scientific world agog with his radical but undeniably successful quantum theory of radiation, a theory which has revolutionized thought in physical science. It was not long before the theory was linked with the electron. In 1905 Einstein proposed a simple quantum theory explanation for a phenomenon long known but little understood—the photoelectric effect, or the emission of electrons from bodies under the action of light. Among the known facts regarding this effect was the observation that the speed or the *kinetic energy* with which the electrons were emitted depended upon the *frequency of the light, but not upon its intensity*. This fact proved impossible to reconcile with any imaginable mechanism for the effect based upon classical laws. The striking nature of this apparent paradox becomes more evident when it is considered that the light from the feeblest possible source, such as a faint star, will eject from a substance electrons having the same kinetic energy as those produced by the most intense arc light. There can be no question of gradual absorption of the light until the requisite energy has been obtained, for in either case emission immediately follows illumination. The only difference is that the arc light produces *more* electrons per second. To a physicist with the viewpoint of the last century it is as though the ripples produced by a raindrop falling in a pond were to cause drops of water to be shot up here and there from the pond to a height of 100 ft, say, and all to the same height no matter how far they happened to be from the source of the ripples. In explanation, Einstein proposed an equation innocent enough when stated in words: that the kinetic energy with which the electron emerges is equal to the energy received from the light minus the work done to escape. The novelty consisted in identifying the energy received from the light with Planck's "quantum" of energy, a discrete bundle of energy. The latter is written as $h\nu$, where h is a universal constant (6.55×10^{-27} erg sec) and ν is the frequency of the light. The amount of energy contained in a quantum then depends only upon the *frequency* of the light, whereas according to the wave theory of radiation it also depends upon the amplitude of the wave (intensity of light). Furthermore, the electron must accept or reject this energy as a unit; it may ignore the quantum completely, but it cannot use part only. The photoelectric effect then could be interpreted rationally in terms of this theory. As added confirmation, the work done by an electron in escaping, on the basis of the Einstein equation, proved to be identical within experimental error with the work w already mentioned as deducible from thermionic emission. Einstein's equation then reads: *kinetic energy* $= h\nu - w$.

THE ATOMIC MODEL OF BOHR

In the hands of Planck and Einstein the phenomena of radiation and photoelectricity thus were explained by the quantum theory, but this theory appeared completely irreconcilable with the wave theory of light which had reached an apparently impregnable position of security during the nineteenth century. How can light radiation consist of waves continuously spreading in all directions and at the same time consist of a collection of bundles of energy, each of which is capable of being delivered intact at any given point? Before a way out of this dilemma could be found, the champions of the wave theory were dismayed to find that overwhelming evidence began to appear in the atomic realm in further support of the quantum theory. In 1913 Niels Bohr put forward a theory of the emission and absorption of light by atoms that explained in remarkable detail the spectrum of hydrogen and ionized helium. His model of the atom as a miniature solar system in which the massive nucleus is the sun and the electrons the planets, now is well known. Although, as a picture, Bohr's atom has faded almost into a mathematical abstraction in the light of present-day quantum mechanics, his fundamental postulate has remained; namely, that the total energy of an atom can change only by an amount equal to a quantum of energy $h\nu$. If the atomic energy increases, an energy $h\nu$ is absorbed; if it decreases, an energy $h\nu$ is liberated. In either case the frequency of radiation absorbed or emitted is perfectly definite and calculable from the relation: $h\nu$ = change in atomic energy. Since the atom then obviously could exist only in discrete "stationary" states of energy, Bohr pictured each electron as having various separate possible orbits of different energies. When an electron jumped from one orbit to another, a definite frequency of radiation corresponding to the resulting change in atomic energy might thus be absorbed or emitted. Confirmation of this idea received support also from the more directly measurable energy required to detach an electron completely from an atom (i. e., to ionize the atom) which energy on the Bohr theory, is calculable as an electron jump from a normal orbit to a very great distance from its nucleus. It was found soon that Bohr's model was inadequate in the case of more complicated atoms; in fact, the atom has shown greater and greater reluctance toward being portrayed in any such simple guise. Of interest here is the fact that a careful study of apparently single spectral lines has exposed a "fine structure" explicable on the quantum basis by attributing to each electron a spin of determinable amount.

Waves Regarded as Particles; The Compton Effect

Probably the most striking application of the quantum theory is shown in the Compton effect. If a homogeneous beam of X rays (which can be shown to consist of waves of equal length and frequency) is allowed to fall upon a solid, a block of carbon for instance, the beam is "scattered" in all directions like a beam of sunlight on paraffin. Analysis of the X rays scattered in a particular direction discloses the curious fact that although a part of the scattered rays retain their original wave length and frequency the remainder are found to possess a definite longer wave length (lower frequency) than the primary rays. (As in all waves, the product of wave length and frequency is equal to the velocity of the wave; hence a longer wavelength has a lower frequency of vibration, and *vice versa.*) These "modified" rays, in the process of being deflected through the scattering angle, have had their quanta of energy reduced in amount. A. H. Compton in 1922 boldly postulated that the fundamental scattering process consisted of a collision between a primary quantum of radiation and an electron, in which collision the usual laws of impact were maintained; namely, conservation of momentum and of energy. As a result of the impact, regarded like that of two billiard balls, the electron is set into motion and thus acquires kinetic energy. This kinetic energy must be furnished by the original quantum, which then leaves the scene of action with less energy; i. e., as a smaller quantum, which in turn means a lower frequency, since the amount of energy in a quantum is proportional solely to its frequency. Thus there is established a remarkable sequence: (1) at the start the frequency of the primary X rays is obtained by measuring their wave length, thus establishing their wave nature; (2) during impact the X ray is treated as a material particle colliding with an admittedly material electron; (3) after impact the frequency again is measured by wave methods. By this method is found complete justification for the assumed character of the impact process, for the theoretical change in frequency observed should depend only (and in a calculable manner) upon the angle of scattering—conclusions which are exactly confirmed by experiment. Furthermore the "recoil" electrons can be detected and shown to have acquired kinetic energy. The question previously asked might now be worded: "When is a wave not a wave?" And the answer, in all seriousness, is: "When it is a particle."

Electric Waves; Wave Mechanics

Considerations such as these led L. de Broglie in 1924 to speculate concerning a possible conception of matter in terms of waves, which idea in any other age would have seemed highly fantastic and metaphysical. Nevertheless, he arrived at a consistent hypothesis, though it required the postulation of waves of a sort different from any which have been observed directly—so-called phase or ψ-waves. This notion was developed by Schrödinger in 1926 into precise mathematical form with noticeable improvement over the Bohr-Sommerfeld theory in the interpretation of spectra. Briefly the "wave-mechanical" theory sets up a second-order differential equation applying to an atom, for instance, that in form resembles a wave equation in sound or in mechanics. Subject to appropriate boundary conditions, solutions of this equation are possible only for certain discrete values of the energy of the atom; for example, the stationary states of Bohr. Thus essentially the scheme is one for determining these same atomic energy states by means of an equation. The equation, be it noted, is a *wave* equation, whereas

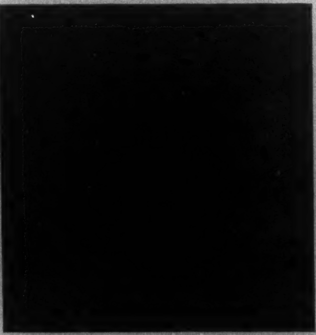

Fig. 2. Diffraction pattern of a narrow beam of X rays on passing through a ZnS crystal

(Friedrich and Knipping)

hitherto only particles had been postulated in an atom. Development in another direction, laying emphasis upon strictly observable quantities such as frequencies instead of hypothetical orbits, led to Heisenberg's matrix theory which is entirely mathematical, using the unusual form of mathematics responsible for its name, and which was shown to agree entirely with the wave-mechanical scheme.

PROOF OF WAVE ASPECT OF ELECTRONS

Now, on the de Broglie wave-mechanical basis, there should be associated with an electron a wave the length of which should be Planck's constant h divided by the momentum of the electron. No direct evidence for such a contention had appeared at that time. The first experimental verification of this property of electrons came, curiously enough, as the result of an accident. In 1927 Davisson and Germer, of the Bell Telephone Laboratories in New York City, were engaged in studying the manner in which electrons were reflected from metal surfaces. A beam of electrons of a given velocity was directed against the face of a piece of nickel in a vacuum and the proportion of electrons reflected at different angles was studied. The electrons were found to be reflected much as might be expected—a large percentage being reflected like perfectly elastic balls (in the manner of rays of light from a mirror) and the number decreasing continuously for angles on either side of the maximum—in other words a fuzzy sort of mirror-like reflection. In preparing for one of the tests, while the nickel specimen was being heated to a high degree in a vacuum to drive out any gases it might contain, the glass container broke and the surface of the nickel was oxidized. After the nickel was treated to remove this oxide layer this particular sample showed a curious type of electron reflection. The reflection was a maximum at the usual angle, to be sure, but there were subsidiary maxima of reflection at other angles on both sides of the usual one. Soon it was shown that this property was occasioned by a crystallization of the nickel, and could be reproduced with any nickel crystal or with crystals of several other metals. Now such a phenomenon is known to occur when light is reflected from the finely ruled surface of a diffraction grating, and it also had been shown by Sir William Bragg to occur when X rays are reflected from the face of a crystal. In the latter case the effect is caused by interference between X ray beams reflected from successive layers of atoms in the crystal. In the cases cited the experiment establishes respectively the wave nature of light and of X rays. The similarity in the case of electron reflection from a metal crystal was striking.

Davisson and Germer, assuming therefore that their discovery was an effect caused by waves, calculated from the angles at which the secondary maxima appeared and from the spacing of the atomic planes in the crystal (known from X ray analysis) the wave length of the hypothetical waves. This wave length agreed accurately with that demanded by de Broglie's theory for electrons; i. e., Planck's constant divided by the electron momentum. Shortly after this discovery G. P. Thomson, the son of J. J. Thomson, obtained a similar effect for electrons shot through thin metallic films. Some of the electrons in the beam were deviated from their straight course, but only in certain preferential directions, so that the resulting pattern of the transmitted beam (in Thomson's experiment registered on a photographic plate) consisted of a central spot about which appeared concentric rings like halos, or in certain cases smaller spots symmetrically arranged at definite distances. Similar patterns produced by X rays had been obtained by Friedrich and Knipping in 1912 and were the first experiments to prove the wave nature of X rays. When E. Rupp in 1929 ruled fine scratches on a plane metal surface and obtained diffraction effects for electrons reflected from this artificial diffraction grating, there was no room for further doubt. Electrons may exhibit the properties of waves, and to the conundrum already propounded concerning radiation must be added a corresponding one. To the question as to when a particle is not a particle comes the answer: when it is a wave.

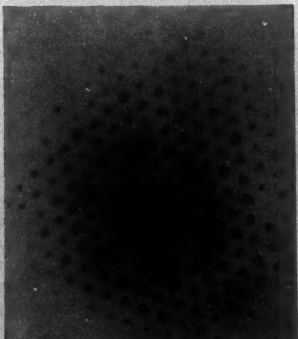

Fig. 3. Diffraction pattern of a narrow beam of electrons on passing through mica

(Kikuchi)

PRESENT STATUS OF ELECTRONIC THEORY

There is after all a sense of relief in finding that both radiation and material particles are consistent in having this dual and mutual aspect. The puzzle raised by the quantum theory in the field of matter is, if not fully understood, at least consistent. We are forced to conclude that the wave and the particle aspects are inseparable and fundamental in nature. In fact, to a high degree of presumption, they are 2 different aspects of the same thing. The question: "Is an electron a wave or a particle?" implies a mutual exclusiveness that does not exist; the electron is both. A similar question would be "Is a musical note in the soprano register or is it pleasing?" Both pitch and quality are attributes of a musical tone. C. G. Darwin suggests that the wave aspect and the particle aspect may bear the same sort of relation to each other as color bears to wave length of light; both are different aspects of the same thing.

Bizarre as this conception of matter and of radiation appears, wave-mechanics have shown its ability to assist in solving many baffling problems regarding the behavior of electrons in addition to its success in spectroscopy. The most successful theory of electrical conduction in solids to date, by Bloch, treats an electric current as the passage of electron waves through the substance. Similarly, Fowler and Nordheim have shown that the laws of thermionic emission may be deduced on the assumption of electron waves breaking through the surface of a body. A signal success of this method was the explanation, hitherto entirely lacking, of electron currents obtained from cold metals by the agency of very intense electric fields, a phenomenon studied experimentally by Millikan and others. A novel property of electron waves that developed in this connection is that there exists a finite chance that an electron wave may escape through a surface barrier even though from the usual standpoint its energy apparently is not equal to the task. This last property of electron waves has within recent years been utilized by Gamov and others to explain radioactive disintegration. Electron waves within a nucleus may have a finite chance of breaking through the bonds that hold them—bonds which would sentence a classical electron particle to the nucleus for life.

In reviewing the status of the electron, it is clear that its properties have been extended considerably beyond those contemplated by its discoverers. It is clear also that in endowing the electron with a spin, a change of mass with velocity, and a wave aspect (although these developments have appeared to be necessary) the mental conception of an electron has lost its vividness. It is no longer, for much of the time at least, simply a tangible unit of electricity. In the light of quantum mechanical theory it shows signs of rapidly becoming a mathematical abstraction. In these respects it is following the trend of the times. Not only has a mental picture of fundamental atomic processes become difficult or even impossible, but the intrinsic precision of the process itself is called into question by the most recent theories. The principle of uncertainty or indeterminism proposed by Heisenberg frankly acknowledges this fact. This principle states that it is impossible simultaneously to determine with perfect exactness both the position and the momentum of an electron. At present the logic behind the *experimental* reasoning in support of this principle is unassailable. The electron is so small that any attempt to determine its position will change its momentum and *vice versa*. For instance, in order to "see" an electron's position accurately it would be necessary to use waves comparable in size to an electron. If longer waves were used an uncertainty in the position would appear, since the position could be determined only to the nearest wave length of the light used. This would necessitate the use of very short waves, such as γ-rays from radioactive substances. Such waves have a large quantum of energy, and upon striking an electron would impart to it a momentum according to the Compton effect; thus an uncertainty would appear in the momentum. It develops that the product of the uncertainty in position and the uncertainty in momentum is of the order of magnitude of Planck's constant h. As a result of this principle and as an inherent property of the present quantum mechanics, in fundamental processes only probabilities can be inferred, never a prediction of certainty. It is believed in some quarters that in this discovery a new fundamental law of nature has been disclosed. Whether this is the case or whether present theories are deficient in this respect is a matter for future investigation to determine. In the meantime, however, no criticism can be offered as to the utility of the new ideas and methods. As theories they are designed to explain and to correlate observed facts and to point the road for further progress. This purpose they are fulfilling admirably.

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The foregoing article is the second in a special series developed under the auspices of the A.I.E.E. committee on education and scheduled for publication month-by-month during 1934. The purpose of the series is to provide, to members of the Institute who are interested in improving their time, some general guidance for contemporary reading and study in several important and rapidly advancing fields of science that are of special significance to electrical engineers. Each of the articles will deal with a specific topic, will present a digest of historical and recent developments and references to current literature, and will be prepared by one of the foremost authorities in its field.

A Symposium on

Wire Transmission of Symphonic Music and its Reproduction in Auditory Perspective

On April 27, 1933, another milestone in the development of the communication art was passed when the music of the Philadelphia Symphony Orchestra was picked up in the Academy of Science Hall in Philadelphia and reproduced in Constitution Hall in Washington, D. C., with a fidelity, depth, and spatial effect that effectively created the illusion of the orchestra's presence behind the stage curtain. To achieve this effect it was necessary that the frequency, intensity, and phase relations of the sound in each ear of each listener be reproduced so accurately as to convey not only the sounds of the various instruments, but also their spatial relations with respect to each other. In this experiment a close approximation to complete facsimile reproduction of symphonic music was obtained by using a 3-channel system, each channel involving its own microphone, amplifier control, transmission, and reproducing equipment. With such a system the auditory illusion was substantially complete and the effect upon the listening audience in the distant hall was essentially the same as though the orchestra had been behind the stage curtains there instead of miles away in another city. Details of the various principles and apparatus involved in the auditory perspective system used in the Philadelphia-Washington experiment are treated in the 6 papers of this symposium appearing on this and the following 23 pages, and on p. 214–19, inclusive, of this issue.

Auditory Perspective —Basic Requirements

The fundamental requirements involved in a system capable of picking up orchestral music, transmitting it a long distance, and reproducing it in a large hall, are discussed in this first paper of the symposium.

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IN THIS ELECTRICAL ERA one is not surprised to hear that orchestral music can be picked up in one city, transmitted a long distance, and reproduced in another. Indeed, most people think such things are commonplace. They are heard every night on the radio. However, anyone who appreciates good music would not admit that listening even to the best radio gives the emotional thrill experienced in the concert hall. Nor is it evident that a listener in a small room ever will be able to get the same effect as that experienced in a large hall, although it must be admitted that such a question is debatable. The proper answer will involve more than a consideration of only the physical factors.

This symposium describes principles and apparatus involved in the reproduction of music in large halls, the reproduction being of a character that may give even greater emotional thrills to music lovers than those experienced from the original music. This statement is based upon the testimony of those who have heard some of the few concerts reproduced by the apparatus which will be described in the papers of this symposium.

It is well known that when an orchestra plays, vibrations which are continually changing in form are produced in the air of the concert hall where the orchestra is located. An ideal transmission and reproducing system may be considered as one that produces a similar set of vibrations in a distant concert hall in which is executed the same time-sequence of changes that takes place in the original hall. Since such changes are different at different positions in the hall, the use of such an ideal system implies that at corresponding positions in the two halls this time-sequence should be the same. Obviously, this never can be true at every position unless the halls are the same size and shape; corresponding positions would not otherwise exist. Let us consider the case where the two halls are the same size and shape and also have the same acoustical properties. Let us designate the first hall in which the music originates by O, and the second one in which the music is reproduced by R. What requirements are necessary to obtain perfect reproduction from O into R such that any listener in any part of R will receive the same sound effects as if he were in the corresponding position in O?

Suppose there were interposed between the orches-

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tra and the audience a flexible curtain of such a nature that it did not interfere with a free passage of the sound, and which at the same time had scattered uniformly over it microphones which would pick up the sound waves and produce a faithful electrical copy of them. Assume each microphone to be connected with a perfect transmission line which terminates in a projector occupying a corresponding position on a similar curtain in hall *R*. By a perfect transmission line is meant one that delivers to the projector electrical energy equal both in form and magnitude to that which it receives from the microphone. If these sound projectors faithfully transform the electrical vibrations into sound vibrations, the audience in hall *R* should obtain the same effect as those listening to the original music in hall *O*.

Theoretically, there should be an infinite number of such ideal sets of microphones and sound projectors, and each one should be infinitesimally small. Practically, however, when the audience is at a considerable distance from the orchestra, as usually is the case, only a few of these sets are needed to give good auditory perspective; that is, to give depth and a sense of extensiveness to the source of the music. The arrangement of some of these simple systems together with their effect upon listeners in various parts of the hall is described in the paper by Steinberg and Snow. (Page 12)

In any practical system it is important to know how near these ideal requirements one must approach before the listener will be aware that there has been any degradation from the ideal. For example, it is well known that whenever a sound is suddenly stopped or started, the frequency band required to transmit the change faithfully is infinitely wide. Theoretically, then, in order to fulfill these ideal requirements for transmitting such sounds, all 3 elements in the transmission system should transmit all possible frequencies without change. Practically, because of the limitations of hearing, this is not necessary. If the intensities of some of the component frequencies required to represent such a change are below the threshold of audibility it is obvious that their elimination will not be detected by the average normal ear. Consequently, for high-grade reproduction of sounds it is obvious that, except in very special cases, the range of frequencies that the system must transmit is determined by the range of hearing rather than by the kind of sound that is being reproduced.

Tests have indicated that, for those having normal hearing, pure tones ranging in frequency from 20 to 20,000 cycles per second can be heard. In order to sense the sounds at either of these extreme limits, they must have very high intensity. In music these frequencies usually are at such low intensities that the elimination of frequencies below 40 cps and those above 15,000 cps produces no detectable difference in the reproduction of symphonic music. These same tests also indicated that the further elimination of frequencies beyond either of these limits did begin to produce noticeable effects, particularly on a certain class of sounds produced in the orchestra. For example, the elimination of all frequencies above 13,000 cps produced a detectable change in the reproduced sound of the snare drum, cymbals, and castanets. Also, the elimination of frequencies below 40 cps produced detectable differences in reproduced music of the base viol, the bass tuba, and particularly of the organ.

Within this range of frequencies the system (the combination of the microphone, transmission line, and loud speaker) should reproduce the various frequencies with the same efficiency. Such a general statement sounds correct, but a careful analysis of it would reveal that when any one tried to build such a system or tried to meet such a requirement he would have great difficulty in understanding what it meant.

For example, for reproducing all the frequencies within this band, a certain system may be said to have a uniform efficiency when it operates between two rooms under the condition that the pressure variation at a certain distance away from the sound projector is the same as the pressure variation at a certain position in front of the microphone. It is obvious, however, that in other positions in the 2 rooms this relation would not in general hold. Also, if the system were transferred into another pair of rooms the situation would be entirely changed. These difficulties and the way they were met are discussed in the papers of this symposium that deal with loud speakers and microphones (p. 17) and with methods of applying the reproducing system to the concert hall (p. 216). It will be obvious from these papers that the criterion for determining the ideal frequency characteristics to be given to the system is arbitrary within certain limits. However, solving the problem according to criteria adopted produced a system that gave very satisfactory results.

Besides the requirement on frequency response just discussed, the system also must be capable of handling sound powers that vary through a very wide range. If this discussion were limited to the type of symphonic music that now is produced by the large orchestras, this range would be about 10,000,000 to 1, or 70 decibels. To reproduce such music then, the system should be capable of handling the smallest amount of power without introducing extraneous noises approaching it in intensity, and also reproduce the most intense sounds without overloading any part of the transmission system. However, this range is determined by the capacities of the musical instruments now available and the man power that conveniently can be grouped together under one conductor. As soon as a system was built that was capable of handling a much wider range, the musicians immediately took advantage of it to produce certain effects that they previously had tried to obtain with the orchestra alone, but without success because of the limited power of the instruments themselves. For these reasons it seems clear that the desirable requirements for intensity range, as well as those for frequency range, are determined largely by the ear rather than by the physical characteristic of any sound. An ideal transmission should, without introducing an extraneous audible sound, be capable of reproducing a sound as faintly as the ear can hear and as loudly as the ear can tolerate. Such a range has been determined with the average normal ear when using pure tones. The results of recent tests are shown in Fig. 1.

The ordinates are given in decibels above the reference intensity which is 10^{-16} watts per square centimeter. The values are for field intensities existing in an air space free from reflecting walls. The most intense peaks in music come in the range between 200 and 1000 cps. Taking an average for this range it may be seen that there is approximately a 100-db range in intensity for the music, provided about 10 db is allowed for the masking of sound in the concert hall even when the audience is quietest.

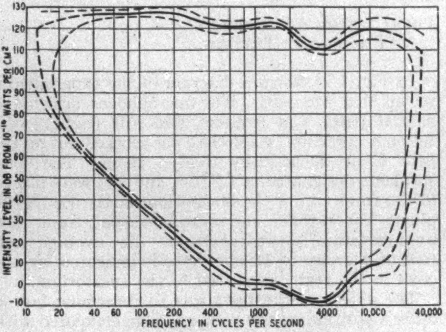

Fig. 1. Limits of audible sound as determined by recent tests

The music from the largest orchestra utilizes only 70 db of this range when it plays in a concert hall of usual size. To utilize the full capabilities of the hearing range the ideal transmission system should add about 10 db on the *pp* side and 20 db on the *ff* side of the range. The capacity of the sound projectors necessary to reach the maximum allowable sound that the ear can tolerate varies with the size of the room. A good estimate can be obtained by the following consideration.

If T is the time of reverberation of the hall in seconds, E the power of the sound source in watts, I the maximum energy density per cubic centimeter in joules, and V the volume of the hall in cubic centimeters, then it is well known teat

$$I = \frac{1}{6 \log_e 10} \cdot \frac{ET}{V} \qquad (1)$$

Measurements have shown that when the sound intensity in a free field reaches about 10^{-4} watts per square centimeter, the average person begins to *feel* the sound. This maximum value is approximately the same for all frequencies in the important audible range. Any higher intensities, and for some persons somewhat lower intensities, become painful and may injure the hearing mechanism. This intensity corresponds to an energy density I of 3×10^{-9} joules. Using this figure as the upper limit to be tolerated by the human ear, then, the maximum power of the sound source must be given by

$$E = 4.1 \times 10^{-8} \frac{V}{T} \qquad (2)$$

For halls like the Academy of Music in Philadelphia and Carnegie Hall in New York City, in which the volume V is approximately 2×10^{10} cubic centimeters and the reverberation time about 2 sec, E, the power of the sound source, is approximately 400 watts. For other halls it may be seen that the power required for this source is proportional to the volume of the hall and inversely proportional to the reverberation time. A person would experience the sense of *feeling* when closer than about 10 meters to such a source of 400 watts power, even in free open space. Hence it would be unwise to have seats closer than 10 or 15 meters from the stage when such powers are to be used.

These, then, are the general fundamental requirements for an ideal transmission system. How near they can be realized with apparatus that we now know how to build will be discussed in the papers included in this symposium.

A system approximately fulfilling these requirements was constructed and used to reproduce the music played by the Philadelphia Orchestra. The first public demonstration was given in Constitution Hall, Washington, D. C., on the evening of April 27, 1933, under the auspices of the National Academy of Sciences. At that time, Dr. Stokowski, Director of the Philadelphia Orchestra, manipulated the electric controls from a box in the rear of Constitution Hall while the orchestra, led by Associate Conductor Smallens, played in the Academy of Music in Philadelphia.

Three microphones of the type described in the paper by Wente and Thuras (p. 17) were placed before the orchestra in Philadelphia, one on each side and one in the center at about 20 ft in front of and 10 ft above the first row of instruments in the orchestra. The electrical vibrations generated in each of these microphones were amplified by voltage amplifiers and then fed into a transmission line which was extended to Washington by means of telephone cable. The construction of these lines, the equipment used with them, and their electrical properties, are described in the paper by Affel, Chesnut, and Mills (p. 28). In Constitution Hall at Washington, D. C., these transmission lines were connected to power amplifiers. The type of power amplifiers and voltage amplifiers used are described in the paper by Scriven (p. 25). The output of these amplifiers fed 3 sets of loud speakers like those described in the paper by Wente and Thuras. They were placed on the stage in Constitution Hall in positions corresponding to the microphones in the Academy of Music, Philadelphia.

Judging from the expression of those who heard this concert, the development of this system has opened many new possibilities for the reproduction and transmission of music that will create even a greater emotional appeal than that obtained when listening to the music coming directly from the orchestra through the air.

Auditory Perspective —Physical Factors

In considering the physical factors affecting it, auditory perspective is defined in this paper as being reproduction which preserves the spatial relationships of the original sounds. Ideally, this would require an infinite number of separate microphone-to-speaker channels; practically, it is shown that good auditory perspective can be obtained with only 2 or 3 channels. This is the second paper in the symposium.

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ABILITY to localize the direction, and to form some judgment of the distance from a sound source under ordinary conditions of listening, are matters of common experience. Because of this faculty an audience, when listening directly to an orchestral production, senses the spatial relations of the instruments of the orchestra. This spatial character of the sounds gives to the music a sense of depth and of extensiveness, and for perfect reproduction should be preserved. In other words, the sounds should be reproduced in true *auditory perspective*.

In the ordinary methods of reproduction, where only a single loud speaking system is used, the spatial character of the original sound is imperfectly preserved. Some of the depth properties of the original sound may be conveyed by such a system,[1] but the directional properties are lost because the audience tends to localize the sound as coming from the direction of a single source, the loud speaker. Ideally, there are 2 ways of reproducing sounds in true auditory perspective. One is binaural reproduction which aims to reproduce in a distant listener's ears, by means of head receivers, exact copies of the sound vibrations that would exist in his ears if he were listening directly. The other method, which was described in the first paper of this series, uses loud speakers and aims to reproduce in a distant hall an exact copy of the pattern of sound vibration that exists in the original hall. In the limit, an infinite number of microphones and loud speakers of infinitesimal dimensions would be needed.

Far less ideal arrangements, consisting of as few as 2 microphone-loudspeaker sets, have been found to give good auditory perspective. Hence, it is not necessary to reproduce in the distant hall an exact copy of the vibrations existing in the original hall. What physical properties of the waves must be preserved then, and how are these properties preserved by various arrangements of 2- and 3-channel loudspeaker reproducing systems? To answer these questions, some very simple localization tests have been made with such systems. Perhaps attention can be focused more easily on their important properties by considering briefly the results of these tests.

LOCALIZATION AFFORDED BY MULTICHANNEL SYSTEMS

In Fig. 1 is shown a diagram of the experimental set-up that was used. The microphones, designated as *LM* (left), *CM* (center), and *RM* (right), were set on a "pick-up" stage that was marked out on the floor of an acoustically treated room. The loud speakers, designated as *LS*, *CS*, and *RS*, were placed in the front end of the auditorium at the Bell Telephone Laboratories and were concealed from view by a curtain of theatrical gauze. The average position of a group of 12 observers is indicated by the cross in the rear center part of the auditorium.

The object of the tests was to determine how a caller's position on the pick-up stage compared with his apparent position as judged by the group of observers in the auditorium listening to the reproduced speech. Words were uttered from some 15 positions on the pick-up stage in random order. The 9 positions shown in Fig. 1 were always included in the 15, the remaining positions being introduced to minimize memory effects. The reproducing system was switched off while the caller moved from one position to the other.

In the first series of tests, the majority of the observers had no previous experience with the set-up. They simply were given a sheet of coördinate paper with a single line ruled on it to indicate the line of the gauze curtain and asked to locate the apparent position of the caller with respect to this line. Following these tests, the observers were permitted to listen to speech from various announced positions on the pick-up stage. This gave them some notion of the approximate outline of what might be called the "virtual" stage. These tests then were repeated. As there was no significant difference in results, the data from both tests have been averaged and are shown in Fig. 1.

The small diagram at the top of Fig. 1 shows the caller's positions with respect to the microphone positions on the pick-up stage. The corresponding average apparent positions when reproduced are shown with respect to the curtain line and the loudspeaker positions. The type of reproduction is indicated symbolically to the right of the apparent position diagrams.

With 3-channel reproduction there is a reasonably

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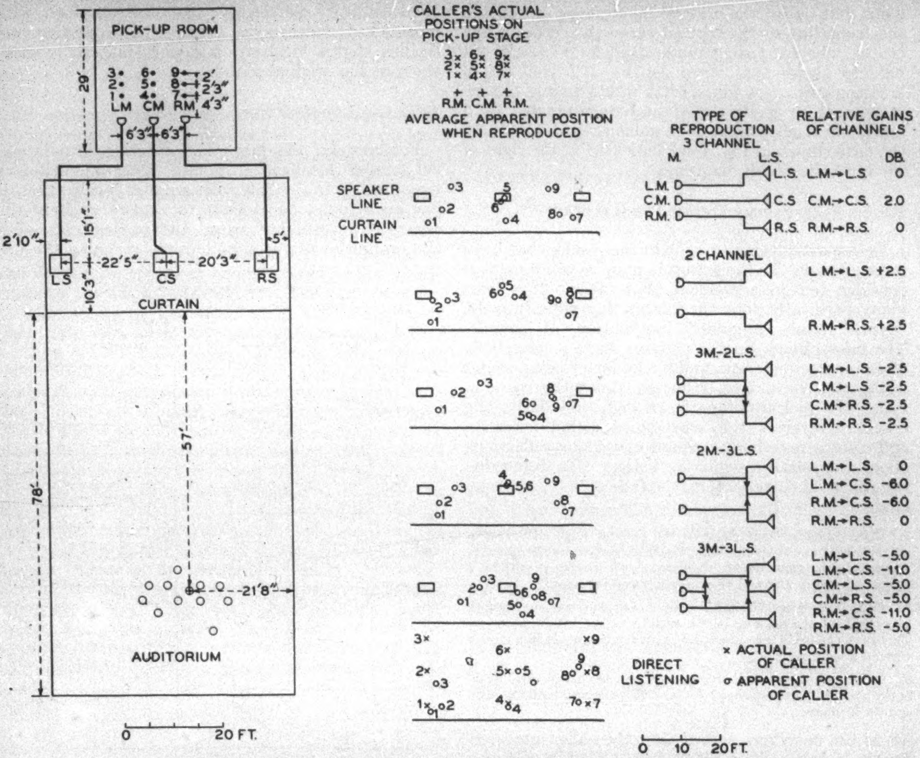
PICK-UP ROOM
29'
3 6 9 2'
2 5 8 2'3"
1 4 7 4'3"
LM CM RM
6'3" 6'3"
15'1"
2'10"
5'
22'5" 20'3"
LS CS RS
10'3"
CURTAIN
57'
78'
21'8"
AUDITORIUM
0 20 FT.
CALLER'S ACTUAL POSITIONS ON PICK-UP STAGE
3× 6× 9×
2× 5× 8×
1× 4× 7×
R.M. C.M. R.M.
AVERAGE APPARENT POSITION WHEN REPRODUCED
SPEAKER LINE
CURTAIN LINE
TYPE OF REPRODUCTION
RELATIVE GAINS OF CHANNELS
3 CHANNEL
M.
L.S.
DB.
L.M.
C.M.
R.M.
L.S.
C.S
R.S.
L.M.→L.S. 0
C.M.→C.S. 2.0
R.M.→R.S. 0
2 CHANNEL
L.M.→L.S. +2.5
R.M.→R.S. +2.5
3M.-2L.S.
L.M.→L.S. -2.5
C.M.→L.S. -2.5
C.M.→R.S. -2.5
R.M.→R.S. -2.5
2M.-3L.S.
L.M.→L.S. 0
L.M.→C.S. -6.0
R.M.→C.S. -6.0
R.M.→R.S. 0
3M.-3L.S.
L.M.→L.S. -5.0
L.M.→C.S. -11.0
C.M.→L.S. -5.0
C.M.→R.S. -5.0
R.M.→C.S. -11.0
R.M.→R.S. -5.0
DIRECT LISTENING
× ACTUAL POSITION OF CALLER
o APPARENT POSITION OF CALLER
0 10 20 FT.

Fig. 1. Diagram of arrangement (left) for sound localization tests and (right) the results obtained

good correspondence between the caller's actual position on the pick-up stage and his apparent position on the virtual stage. Apparent positions to the right or left correspond with actual positions to the right or left, and apparent front and rear positions correspond with actual front and rear positions. Thus the system afforded lateral or "angular" localization as well as fore and aft or "depth" localization. For comparison, there is shown in the last diagram the localization afforded by direct listening. The crosses indicate a caller's position in back of the gauze curtain and the circles indicate his apparent position as judged by the observers listening to his speech directly. In both cases, as the caller moved back in a straight line on the left or right side of the stage, he appeared to follow a curved path pulling in toward the rear center; e. g., compare the caller positions 1, 2, 3, with the apparent positions 1, 2, 3. This distortion was somewhat greater for 3-channel reproduction than for direct listening.

The results obtained with the 2-channel system show 2 marked differences from those obtained with 3-channel reproduction. Positions on the center line of the pick-up stage (i. e., 4, 5, 6) all appear in the rear center of the virtual stage, and the virtual stage depth for all positions is reduced. The virtual stage width, however, is somewhat greater than that obtained with 3-channel reproduction.

Bridging a third microphone across the 2-channel system had the effect of pulling the center line positions 4, 5, 6, forward, but the virtual stage depth remained substantially that afforded by 2-channel reproduction, while the virtual stage width was decreased somewhat. In this and the other bridged arrangements the bridging circuits employed amplifiers, as represented by the arrows in Fig. 1, in such a way that there was a path for speech current only in the indicated direction.

Bridging a third loud speaker across the 2-channel system had the effect of increasing the virtual stage depth and decreasing the virtual stage width, but positions on the center line of the pick-up stage appeared in the rear center of the virtual stage as in 2-channel reproduction.

Bridging both a third microphone and a third loud speaker across the 2-channel system had the effect of reducing greatly the virtual stage width. The width could be restored by reducing the bridging gains, but fading the bridged microphone out caused the front line of the virtual stage to recede at the center, whereas fading the bridged loud speaker out reduced the virtual stage depth. No fixed set of bridging gains was found that would enable the arrangement to create the virtual stage created by 3 independent channels. The gains used in obtaining the data shown in Fig. 1 are indicated at the right of the symbolic circuit diagrams.

Factors Affecting Depth Localization

Before attempting to explain the results that have been given in the foregoing, it may be of interest to consider certain additional observations that bear more specifically upon the factors that enter into the "depth" and "angular" localization of sounds. The microphones on the pick-up stage receive both direct and reverberant sound, the latter being sound waves that have been reflected about the room in which the pick-up stage is located. Similarly, the observer receives the reproduced sounds directly and also as reverberant sound caused by reflections about the room in which he listens. To determine the effects of these factors, the following 3 tests were made:

1. Caller remained stationary on the pick-up stage and close to microphone, but the loudness of the sound received by the observer was reduced by gain control. This was loudness change without a change in ratio of direct to reverberant sound intensity.

2. Caller moved back from microphone, but gain was increased to keep constant the loudness of the sound received by the observer. This was a change in the ratio of direct to reverberant sound intensity without a loudness change.

3. Caller moved back from microphone, but no changes were made in the gain of the reproducing system. This changed both the ratio and the loudness.

All of the observers agreed that the caller appeared definitely to recede in all 3 cases. That is, either a reduction in loudness or a decrease in ratio of direct to reverberant sound intensity, or both, caused the sound to appear to move away from the observer. Position tests using variable reverberation with a given pick-up stage outline showed that increasing the reverberation moved the front line of the virtual stage toward the rear, but had slight effect upon the rear line. When the microphones were placed outdoors to eliminate reverberation, reducing the loudness either by changing circuit gains or by increasing the distance between caller and microphone moved the whole virtual stage farther away. It is because of these effects that all center line positions on the pick-up stage appeared at the rear of the virtual stage for 2-channel reproduction.

It has not been found possible to put these relationships on a quantitative basis. Probably a given loudness change, or a given change in ratio of direct to reverberant sound intensity, causes different sensations of depth depending upon the character of the reproduced sound and upon the observer's familiarity with the acoustic conditions surrounding the reproduction. Since the depth localization is inaccurate even when listening directly, it is difficult to obtain sufficiently accurate data to be of much use in a quantitative way. Because of this inaccuracy, good auditory perspective may be obtained with reproduced sounds even though the properties controlling depth localization depart materially from those of the original sound.

Angular Localization

Fortunately, the properties entering into lateral or angular localization permit more quantitative treatment. In dealing with angular localization, it has been found convenient to neglect entirely the effects of reverberant sound and to deal only with the properties of the sound waves reaching the observer's ears without reflections. The reflected waves or reverberant sounds do appear to have a small effect on angular localization, but it has not been found possible to deal with such sound in a quantitative way. One of the difficulties is that, because of differences in the build-up times of the direct and reflected sound waves, the amount of direct sound relative to reverberant sound reaching the observer's ears for impulsive sounds such as speech and music is much greater than would be expected from steady state methods of dealing with reverberant sound.

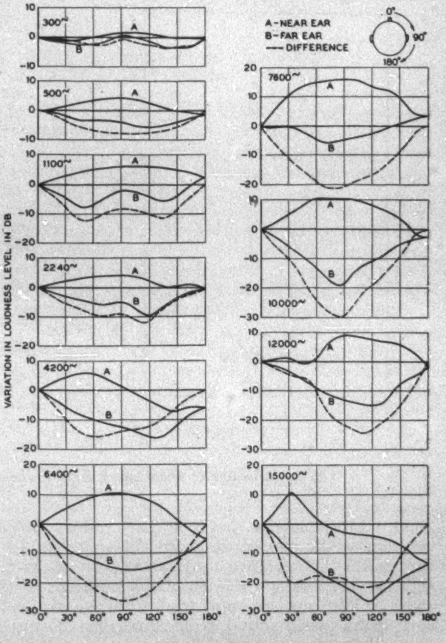

Fig. 2. Variation in loudness level as a sound source is rotated in a horizontal plane around the head

For the case of a plane progressive wave from a single sound source, and where the observer's head is held in a fixed position, there are apparently only 3 factors that can assist in angular localization: namely, phase difference, loudness difference, and quality difference between the sounds received by the 2 ears.

In applying these factors to the localization of sounds from more than one source, as in the present case, the effects of phase differences have been neglected. It is difficult to see how phase differences in this case can assist in localization in the ordinary way. The 2 remaining factors, loudness and quality differences, both arise from the directivity of hearing. This directivity probably is due in part to the shadow and diffraction effects of the head and to the differences in the angle subtended by the ear openings. Measurements of the directivity with a source of pure tone located in various positions around the head in a horizontal plane have been reported by Sivian and White.[2] From these measurements, the loudness level differences between near and far ears have been determined for various frequencies. These differences are shown in Fig. 2 from which, using the pure tone data given, similar loudness level differences for complex tones may be calculated. Such calculated differences for speech are shown in Fig. 3.

As may be inferred from the varying shapes of the curves of Fig. 2, the directive effects of hearing introduce a frequency distortion more or less characteristic of the direction from which the sound comes. Thus the character or quality of complex sounds varies with the angle of the source. There are quality differences at each ear for various angles of source, and quality differences between the two ears for a given angle of source. In Fig. 4 is shown the frequency distortion at the right ear when a source of sound is moved from a position on the right to one on the left of an observer. It is a graph of the "difference" values of Fig. 2 for an angle of 90 deg. Frequencies above 4,000 cycles per second are reduced by as much as 15 to 30 decibels. This amount of distortion is sufficient to affect materially the quality of speech, particularly as regards the loudness of the sibilant sounds.

Reference to the difference curve of Fig. 3 shows that if, for example, a source of speech is 20 deg to the right of the median plane the speech heard by the right ear is 3 db louder than that heard by the left ear. A similar difference exists when the angle is 167 deg. Presumably, when the right ear hears speech 3 db louder than the left, the observer localizes the sound as coming from a position 20 deg or 167 deg to the right, depending upon the quality of the speech. If this be assumed to be true, even though the difference is caused by the combination of sounds of similar quality from several sources, it should be possible to calculate the apparent angle.

LOUDNESS THEORY OF LOCALIZATION

Upon this assumption the apparent angle of the source as a function of the difference in decibels between the speech levels emitted by the loud speakers of the 2- and 3-channel systems has been calculated. Each loud speaker contributes an amount of direct sound loudness to each ear, depending upon its distance from, and its angular position with respect to, the observer. These contributions were combined on a power basis to give a resultant loudness of direct sound at each ear, from which the difference in loudness between the 2 ears was determined. The calculated results for the 2- and 3-channel systems are shown by the solid lines in Fig. 5. The y axis shows the apparent angle, positive angle being measured in a clockwise direction. The x axis shows the difference in decibels between the speech levels from the right and left loud speakers. The points are observed values taken from Fig. 1. The observed apparent angles were obtained directly from the average observer's location and the average apparent positions shown in Fig. 1. The speech levels from each of the loud speakers were calculated for each position on the pick-up stage. This was done by assuming that the waves arriving at the microphone had relative levels

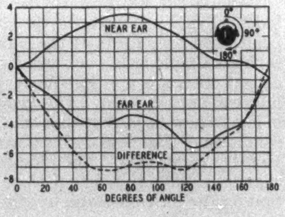

Fig. 3. Variation in loudness as a speech source is rotated in a horizontal plane around the head

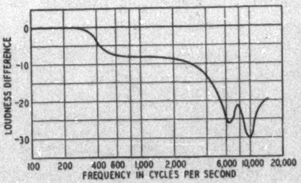

Fig. 4. Loudness difference produced in the right ear when a source of pure tone is moved from a position on the right to the left of an observer

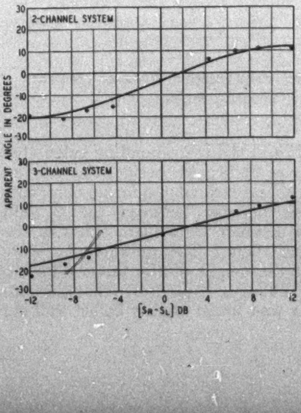

Fig. 5. Calculated and observed apparent angles for 2- and 3-channel reproduction

inversely proportional to the squares of the distances traversed. By correcting for the angle of incidence and for the known relative gains of the systems, the speech levels from the loud speakers were obtained.

A comparison of the observed and calculated results seems to indicate that the loudness difference at the 2 ears accounts for the greater part of the apparent angle of the reproduced sounds. If this is true, the angular location of each position on the virtual stage results from a particular loudness difference at the 2 ears produced by the speech coming from the loud speakers. When 3 channels are used a definite set of loud speaker speech levels exists for each position on the pick-up stage. To create these same sets of loud speaker speech levels with the bridging arrangement of 3-microphones 3-loud speakers already discussed, it would be necessary to change the bridging gains for each position on the pick-up stage. Hence it could not be expected that the arrangement as used (i. e., with fixed gains) would create a virtual stage identical with that created by 3-channel reproduction. However, with proper technique, bridging arrangements on a given number of channels can be made to give better reproduction than would be obtained with the channels alone.

Experimental Verification of Theory

Considerations of loudness difference indicate that all caller positions on the pick-up stage giving the same relative loud speaker outputs should be localized at the same virtual angle. The solid lines of Fig. 6 show a stage layout used to test this hypothesis with the 2-channel system. All points on each line have a constant ratio of distances to the microphones. The resulting direct sound differences in pressure expressed in decibels and the corresponding calculated apparent angles are indicated beside the curves. The apparent angles were calculated for an observing position on a line midway between the 2 loud speakers but at a distance from them equal to the separation between them. The microphones were turned face up at the height of the talker's lips to eliminate quality changes caused by changing incidence angle. It was found that a caller walking along one of these lines maintained a fairly constant virtual angle. For caller positions far from the microphones the observed angles were somewhat greater than those computed. For highly reverberant conditions, the tendency was toward greater calculated than observed angles. Reverberation also decreased the accuracy of localization.

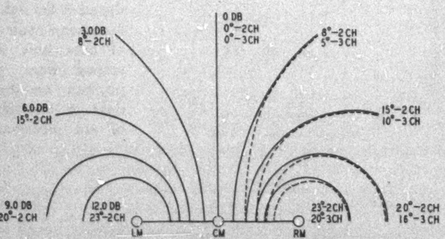

Fig. 6. Pick-up stage contour lines of constant apparent angle

A change of relative channel gain caused a change in virtual angle as would be expected from loudness difference considerations. For instance, if the caller actually walked the left 3-db line, he seemed to be on the 6-db line when the left channel gain was raised 3 db. Many of the effects of moving about the pick-up stage could be duplicated by volume control manipulation as the caller walked forward and backward on the center path. With a bridged center microphone substituted for the 2 side microphones similar effects were possible and, in addition, the caller by speaking close to the microphone could be brought to the front of the virtual stage.

For observing positions near the center of the auditorium the observed angles agreed reasonably well with calculations based only upon loudness differences. As the observer moved to one side, however, the virtual source shifted more rapidly toward the nearer loud speaker than was predicted by the computations. This was true of reproduction in the auditorium, both empty and with damping simulating an audience, and outdoors on the roof. Computations and experiment also show a change in apparent angle as the observer moves from front to rear, but its magnitude is smaller than the error of an individual localization observation. Consequently, observers in different parts of the auditorium localize given points on the pick-up stage at different virtual angles.

Because the levels at the 3 microphones are not independent, and because the desired contours depend upon the effects at the ears, a 3-channel stage is not as simple to lay out as a 2-channel stage. For a given observing position, however, a set of contour lines can be calculated. The dashed lines at the right of Fig. 6 show 4 contours thus calculated for the circuit condition of Fig. 1 and the observing position previously mentioned. The addition of the center channel reduces the virtual angle for any given position on the pick-up stage by reducing the resultant loudness difference at the ears. Although the 3-channel contours approach the 2-channel contours in shape at the back of the stage, a given contour results in a greater virtual angle for 2- than for 3-channel reproduction.

Similar effects were obtained experimentally. As in 2-channel reproduction, movements of the caller could be simulated by manipulation of the channel gains. From an observing standpoint the 3-channel system was found to have an important advantage over the 2-channel system in that the shift of the virtual position for side observing positions was smaller.

Effects of Quality

If the quality from the various loud speakers differs, the quality of sound is important to localization. When the 2-channel microphones were so arranged that one picked up direct sound and reverberation while the other picked up mostly reverberation, the virtual source was localized exactly in the "direct" loud speaker until the power from the "reverberant" loud speaker was from 8 to 10 db greater. In general, localization tends toward the channel giving most natural or "close-up" reproduction, and this effect can be used to aid the loudness differences in producing angular localization.

PRINCIPAL CONCLUSIONS

The principal conclusions that have been drawn from these investigations may be summarized as follows:

1. Of the factors influencing angular localization, loudness difference of direct sound seems to play the most important part; for certain observing positions the effects can be predicted reasonably well from computations. When large quality differences exist between the loudspeaker outputs, the localization tends toward the more natural source. Reverberation appears to be of minor importance unless excessive.

2. Depth localization was found to vary with changes in loudness, the ratio of direct to reverberant sound, or both, and in a manner not found subject to computational treatment. The actual ratio of direct to reverberant sound, and the change in the ratio, both appeared to play a part in an observer's judgment of stage depth.

3. Observers in various parts of the auditorium localize a given source at different virtual positions, as is predicted by loudness computations. The virtual source shifts to the side of the stage as the observer moves toward the side of the auditorium. Although quantitative data have not been obtained, qualitative data on these effects indicate that the observed shift is considerably greater than that computed. Moving backward and forward in the auditorium appears to have only a small effect on the virtual position.

4. Because of these physical factors controlling auditory perspective, point-for-point correlation between pick-up stage and virtual stage positions is not obtained for 2- and 3-channel systems. However, with stage shapes based upon the ideas of Fig. 7, and with suitable use of quality and reverberation, good auditory perspective can be produced. Manipulation of circuit conditions probably can be used advantageously to heighten the illusions or to produce novel effects.

5. The 3-channel system proved definitely superior to the 2-channel by eliminating the recession of the center-stage positions and in reducing the differences in localization for various observing positions. For musical reproduction, the center channel can be used for independent control of soloist renditions. Although the bridged systems did not duplicate the performance of the physical third channel, it is believed that with suitably developed technique their use will improve 2-channel reproduction in many cases.

6. The application of acoustic perspective to orchestral reproduction in large auditoriums gives more satisfactory performance than probably would be suggested by the foregoing discussions. The instruments near the front are localized by every one near their correct positions. In the ordinary orchestral arrangement, the rear instruments will be displaced in the reproduction depending upon the listener's position, but the important aspect is that every auditor hears differing sounds from differing places on the stage and is not particularly critical of the exact apparent positions of the sounds so long as he receives a spatial impression. Consequently 2-channel reproduction of orchestral music gives good satisfaction, and the difference between it and 3-channel reproduction for music probably is less than for speech reproduction or the reproduction of sounds from moving sources.

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Auditory Perspective —Loud Speakers and Microphones

In ordinary radio broadcast of symphony music, the effort is to create the effect of taking the listener to the scene of the program, whereas in reproducing such music in a large hall before a large gathering the effect required is that of transporting the distant orchestra to the listeners. Lacking the visual diversion of watching the orchestra play, such an audience centers its interest more acutely in the music itself, thus requiring a high degree of perfection in the reproducing apparatus both as to quality and as to the illusion of localization of the various instruments. Principles of design of the loud speakers and microphones used in the Philadelphia-Washington experiment are treated at length in this, the third paper of this symposium.

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AS EARLY AS 1881 a large scale musical performance was reproduced by telephone instruments at the Paris Electrical Exhibition. Microphones were placed on the stage of the Grand Opera and connected by wires to head receivers at the exposition. It is interesting to note that separate channels were provided for each ear so as to give to the music perceived by the listener the "character of relief and localization." With head receivers it is necessary to generate enough sound of audible intensity to fill only a volume of space enclosed between the head receiver and the ear. As no amplifiers were available, the production of enough sound to fill a large auditorium would have been entirely outside the range of possibilities. With the advent

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1. Bell Telephone Laboratories, Inc.

of telephone amplifiers, microphone efficiency could be sacrificed to the interest of good quality where, as in the reproduction of music, this was of primary interest. When amplifiers of greater output power capacity were developed, loud speakers were introduced to convert a large part of the electrical power into sound so that it could be heard by an audience in a large auditorium. Improvements have been made in both microphones and loud speakers, resulting in very acceptable quality of reproduction of speech and music; as is found, for instance, in the better class of motion picture theaters.

In the reproduction, in a large hall, of the music of a symphony orchestra the approach to perfection that is needed to satisfy the habitual concert audience undoubtedly is closer than that demanded for any other type of musical performance. The interest of the listener here lies solely in the music. The reproduction therefore should be such as to give to a lover of symphonic music esthetic satisfaction at least as great as that which would be given by the orchestra itself playing in the same hall. This is more than a problem of instrument design, but this paper will be restricted to a discussion of the requirements that must be met by the loud speakers and microphones, and to a description of the principles of design of the instruments used in the transmission of the music of the Philadelphia Orchestra from Philadelphia to Constitution Hall in Washington. Some of the requirements are found in the results of measurements that have been made on the volume and frequency ranges of the music produced by the orchestra.

GENERAL CONSIDERATIONS

The acoustic powers delivered by the several instruments of a symphony orchestra, as well as by the orchestra as a whole, have been investigated by Sivian, Dunn, and White. Figure 1 was drawn on the basis of the values published by them.[1] The ordinates of the horizontal lines give the values of the peak powers within the octaves indicated by the positions of the lines. For a more exact interpretation of these values the reader is referred to the original paper, but the chart here given will serve to indicate the power that a loud speaker must be capable of delivering in the various frequency regions, if the reproduced music is to be as loud as that given by the orchestra itself. However, it was the plan in the Philadelphia-Washington experiment to reproduce the orchestra, when desired, at a level 8 or 10 db higher, so that with 3 channels each loud speaking system had to be able to deliver 2 or 3 times the powers indicated in Fig. 1. Sivian, Dunn, and White also found that for the whole frequency band the peak powers in some cases reached values as high as 65 watts. In order to go 8 db above this value, each channel would have to be capable of delivering in the neighborhood of 135 watts.

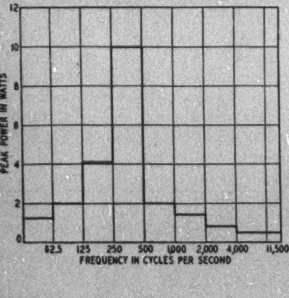


Fig. 1. Peak powers delivered by an orchestra within various frequency regions

The chart (Fig. 1) shows that the orchestra delivers sound of comparable intensity throughout practically the whole audible range. Although it is conceivable that the ear would not be capable of detecting a change in quality if some of the higher or lower frequencies were suppressed, measurements published by W. B. Snow[2] show that for any change in quality in any of the instruments to be undetectable the frequency band should extend from about 40 to about 13,000 cps. The necessary frequency ranges that must be transmitted to obviate noticeable change in quality for the different orchestral instruments are indicated in the chart of Fig. 2, which is taken from the paper by Snow.

Thus far only the sound generated by the orchestra itself has been considered. However, it is well known that the esthetic value of orchestral music in a concert hall is dependent to a very great extent upon the acoustic properties of the hall. At first thought one might be inclined to leave this out of account in considering the reproduction by a loud speaking system, as one should normally choose a hall known to have satisfactory acoustics for an actual orchestra. There would be no further problem in this if the orchestral instruments and the loud speaker radiated the sound uniformly in all directions, but some of the important instruments are quite directive; i. e., they radiate much the greater portion of their sound through a relatively small angle. As an example, a polar diagram giving the relative intensities of the sound radiated in various directions by the violin is given in Fig. 3, which is taken from a paper published by Backhaus.[3] The directional characteristics of some of the instruments is one of the chief reasons why the music from an orchestra does not sound the same in all parts of a concert hall. The music which we hear comes to us in part directly and in part indirectly; i. e., after one or more reflections from the walls. Both contribute to the esthetic value of the music. The ratio of the direct to the indirect sound, which has been designated by Hughes[4] as the *acoustic ratio*, is to a first approximation inversely proportional to the product of the reverberation time and the angle through which the sound is radiated.[5] For a steady tone by far the greater part of the intensity at a given point in a hall remote from the source is attributable to the indirect sound. However, inasmuch as many of the tones of a musical selection are of short duration, the direct sound is of great importance; it is this sound alone which enables us to localize the source. So far as this ratio is concerned, a decrease in the radiating angle of a loud speaker is equivalent to a reduction in the reverberation time of the hall. The effect on the music, however, is not entirely equivalent, for the rate of decay of sound in the room is unaltered by a change in directivity of the source, as this depends only on the reverberation time.

As already pointed out, some of the instruments of the orchestra are quite directive and others are nondirectional. In general, it may be said that the instruments of lower register are less directive than those of higher register. To have each instrument as reproduced by the loud speaker sound just as the instrument itself would sound in the same hall, the loud speaker would have to reproduce the music from each instrument with a directivity corresponding to that of the instrument itself. This manifestly is impossible. The best that can be hoped for is a compromise. Let the loud speaking system be designed so that it is nondirective for the lower frequencies, and at the higher frequencies it will radiate the sound through a larger angle than the most directive of the instruments and through a smaller angle than the least directive. Although this compromise means that the individual instruments will not sound exactly like the originals, it carries with it one advantage: At all the seats in the hall included in the radiating angle and at a given distance from the loud speaker the music may be heard to equal advantage, whereas with the orchestra itself the most desirable seats comprise only a certain portion of the hall. The optimum radiating angle is largely a matter of judgment; if it is too small the music will lack the spatial quality experienced at indoor concerts; if it is too large there will be a loss in definition.

There is another respect in which the directivity of the source can greatly affect the tone quality. Most loud speakers radiate tones of low frequency through a relatively large angle, but as the frequency is increased this angle becomes smaller and smaller. Under this condition the relation between the intensities of the high and low frequency tones as received directly will be different for almost all parts of the hall. Hence, even with equalization by electrical networks, the reproduction at best can be good only at a few places in the hall. Therefore, the sound radiated not only should be contained within a certain solid angle, but the radiation throughout this angle should be uniform at all frequencies.

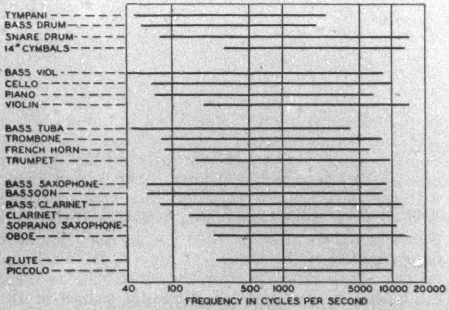


Fig. 2. Frequency transmission range required to produce no noticeable distortion for orchestral instruments

The Loud Speaker

At present 2 kinds of loud speakers are in wide commercial use, the direct radiating and the horn types. Each has its merits, but the latter was used in the Philadelphia-Washington experiment because it appears to have definite advantages where such large amounts of power are to be radiated. The horn type can be given the desired directive properties more readily, and higher values of efficiency throughout a wide frequency range are more easily realized. In consideration of the large power requirements, high efficiency is of special importance because it will keep to the lowest possible value the power capacity requirements of the amplifiers and because, with the heating proportional to one minus the efficiency, the danger of burning out the receiving units is reduced.

For efficiently radiating frequencies as low as 40 cps, a horn of large dimensions is required. In order that the apparatus may not become too unwieldy the folded type of horn is preferable, but a large folded horn transmits high frequency tones very inefficiently. As actually used, therefore, the loud speaker was constructed in 2 units: one for the lower and the other for the higher frequencies, an electrical network being used to divide the current into 2 frequency bands, the point of division being about 300 cps.

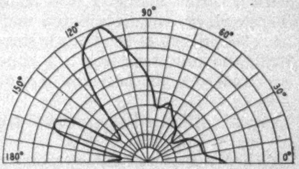


Fig. 3. Variation of intensity with direction of the sound radiated by a violin (660 cps)

The Low Frequency Horn

When moderate amounts of power are transmitted through a horn the sound waves will suffer very little distortion, but when the power per unit area becomes large, second-order effects, usually neglected in considering waves of small amplitude, must be taken into account. The transmission of waves of large amplitude through an exponential horn has been investigated theoretically by M. Y. Rocard.[6] His investigation shows that if W watts are transmitted through the throat of an exponential horn a second harmonic of intensity RW will be generated, where R is given by the relation

$$R = \frac{(\gamma + 1)^2 f^2 \times 10^7 W}{2\rho c^3 f_0^2 A}, \tag{1}$$

in which f is the frequency of the fundamental, f_0

the cut-off frequency of the horn, c the velocity of sound, ρ the density of air, and A the area of the throat of the horn, all expressed in cgs units. It may be noted that the intensity of the harmonic increases with the ratio of the frequency to the cut-off frequency of the horn; this is another argument against attempting to cover too wide a range of frequencies with a single horn. In Fig. 1 it is shown that in the region of 200 cps the orchestra gives peak powers of about 10 watts. If, therefore, 30 watts be set as the limit of power that the horn is to deliver at 200 cps, 32 cps as the cut-off frequency of the horn, and 30 db below the fundamental be assumed as the limit of tolerance of a second harmonic, from eq 1 a throat diameter of about 8 in. is determined.

If the radiation resistance at the throat of a horn is not to vary appreciably with frequency, the mouth opening must be a substantial fraction of a wave length. This condition calls for an unusually large horn if frequencies down to 40 cps and below are to be transmitted. However, the effect of variations in radiation resistance on sound output can be kept down to a relatively small value if the receiving unit is properly designed. This will be explained in the next section. The low frequency horn used in these reproductions has a mouth opening of about 25 sq ft. As computed from well-known formulas [7] for the exponential horn the impedance of this horn with a throat diameter of 8 in. is shown in Fig. 4. These curves were computed under the assumption that the mouth of the horn is surrounded by a plane baffle of infinite extent, a condition closely approximated if the horn rests on a stage floor.

LOW FREQUENCY RECEIVING UNIT

When a moving coil receiving unit, coupled to a horn, is connected to an amplifier having an output resistance equal to $n-1$ times the damped resistance R of the driving coil, it can easily be shown that the sound power output is

$$P = \frac{\left(\frac{EBLT}{nR}\right)^2 r \times 10^{-9}}{\left[T^2r + \frac{B^2L^2 \times 10^{-9}}{nR}\right]^2 + [x_d + T^2x]^2} \text{ watts} \tag{2}$$

where E is the open circuit voltage of the amplifier, L the length of wire in the receiver coil, T the ratio of the area of the diaphragm to the throat area of the horn, $r + jx$ the throat impedance of the horn, and x_d the mechanical reactance of the diaphragm and coil, the mechanical resistance of which is assumed to be negligibly small. From Fig. 4 it may be seen that the mean value of x increases as the frequency decreases to a value below 40 cps, and that x is smaller than r except at the very lowest frequencies. If, therefore, the stiffness of the diaphragm be adjusted so that x_d is equal to T^2 times the mean value of x at 40 cps, the second term in the denominator may be neglected without much error because it will have but little effect upon the sound output except at the higher frequencies, where the mass reactance of the coil and diaphragm may have to be taken into account.

If minimum variations in sound output are desired for variations in r,

$$\frac{B^2L^2 10^{-9}}{nRT^2} = r_0 \tag{3}$$

where r_0 is equal to the geometric mean value of r, which is approximately equal to $A\rho c$.
If α is the ratio of the resistance at any frequency to the mean value, and if the second term in the denominator is neglected, eq 2 becomes

$$P = \frac{E^2}{nR} \frac{\alpha}{(1 + \alpha)^2} \tag{4}$$

In Fig. 4 it is shown that above 35 cps α has extreme values of 2.75 and 0.36, at which points there will

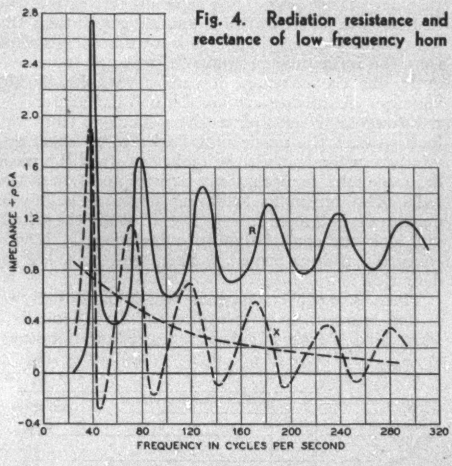


Fig. 4. Radiation resistance and reactance of low frequency horn

be minimum values in P, but these minimum values will not lie more than 1 db below the maximum values. Hence, if the receiver satisfies the condition of eq 3, the extreme variations in the sound output will not exceed 1 db, although the horn resistance varies by a factor of 7.5. Also it may be stated here that when the condition of eq 3 is satisfied the horn is terminated at the throat end by a resistance equal to the surge resistance of the horn. Thus eq 3 establishes a condition of minimum values in the transient oscillations of the horn.

The mean motional impedance of the loud speaker is $\frac{B^2L^2 \times 10^{-9}}{T^2r_0}$ which, from eq 3, is equal to nR. The condition of eq 3 therefore specifies that the efficiency of the loud speaker shall be $\frac{n}{n+1}$. The maximum power that an amplifier can deliver without introducing harmonics exceeding a specified value is a function of the impedance into which it operates. Therefore, to obtain the maximum acoustic power for a specified harmonic content, the load impedance should have the value for which the product of the loud speaker efficiency and the power capacity of the amplifier has a maximum value. This optimum value of load impedance for the amplifier and loud speaker used in the Philadelphia-Washington experiments was found to be about 2.25 times the output impedance of the amplifier; the corresponding value of n then is 2.6 and the required efficiency 72 per cent. For best operating condition a definite value of receiver efficiency thus is specified.

The receiver may be made to satisfy the foregoing conditions regardless of the value of T, the ratio of diaphragm area to throat area. The area of the diaphragm has, however, a definite relation to the maximum power that the receiver can deliver at the low frequencies. The peak power delivered by the receiver is equal to $T^2\alpha r_0\xi^2\omega^2 \times 10^{-7}$ peak watts where ξ is the maximum amplitude of motion of the diaphragm. Figure 1 shows that in the region lying between 40 and 60 cps, peak powers reach a value of from 1 to 2 watts. However, the low frequency tones of an orchestra are undesirably weak and may advantageously be reproduced at a relatively higher level. Therefore it was decided to construct the loud speaker to be able to deliver 25 watts in this region.

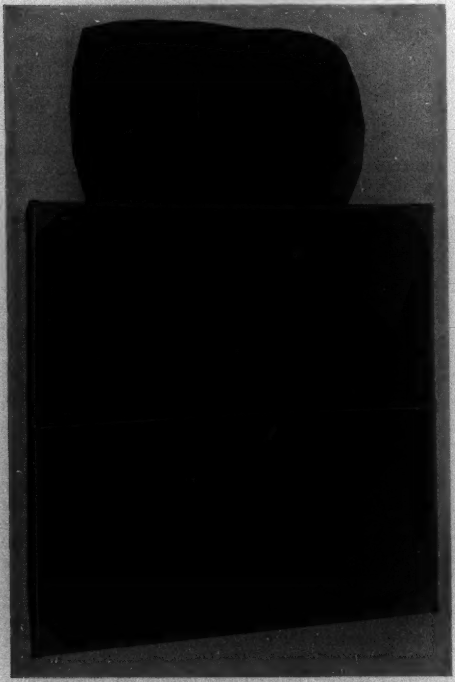


Fig. 5. Special loud speaker developed for auditory perspective experiment

As the coil moves out of its normal position in the air gap, the force factor varies. Harmonics thus will be generated, the intensities of which increase with increasing amplitude. A limit to the maximum value of the amplitude ξ thus is set by the harmonic distortion that one is willing to tolerate. In this receiver the maximum value of ξ was taken equal to 0.060 in. Figure 4 shows that $\alpha\omega^2$ has a minimum value at about 50 cycles, where α is equal to about 0.4. These values give a ratio of 4.5 for T.

Inasmuch as $R = \frac{\sigma L^2}{v}$, where σ is the resistivity of the wire used for the coil and v the volume of the coil, from eq 3 is obtained

$$B^2v = n\sigma T^2 r_0 10^9 \qquad (5)$$

The first member gives the total magnetic energy that must be set up in the region occupied by the driving coil. This value is fixed by the fact that all factors in the second member are specified. The same performance is obtained with a small coil and high flux density as with a large coil and low flux density, provided B^2v is held fixed, but the coil in any case should not be made so small that it will be incapable of radiating the heat generated within it without danger of overheating, nor so large that the mass reactance of the coil will reduce the efficiency at the higher frequencies.

This receiver unit, when constructed according to the above principles and when connected to an amplifier and a horn in the specified manner, should be capable of delivering power 3 or 4 times that delivered by the orchestra in the frequency region lying between 35 and 400 cps, with an efficiency of about 70 per cent, and with a variation in sound output for a given input power to the amplifier of not more than 1 db throughout this range.

THE HIGH FREQUENCY HORN

It is well known that a tapered horn of the ordinary type has a directivity which varies with frequency. Sound of low frequency is projected through a relatively large angle. As the frequency is increased this angle decreases progressively until, at frequencies for which the wave length is small compared with the diameter of the mouth opening, the sound beam is confined to a very narrow angle about the axis of the horn.

If we had a spherical source of sound (i. e., a source consisting of a sphere, the surface of which has a radial vibratory motion equal in phase and amplitude at every point of the surface), sound would be radiated uniformly outward in all directions; or, if we had only a portion of a spherical surface over which the motion is radial and uniform, uniform sound radiation still would prevail throughout the solid angle subtended at the center of curvature by this portion of the sphere, provided its dimensions were large compared with the wave length. Throughout this region the sound would appear to originate at the center of curvature. Hence, for the ideal distribution of a spherical source within

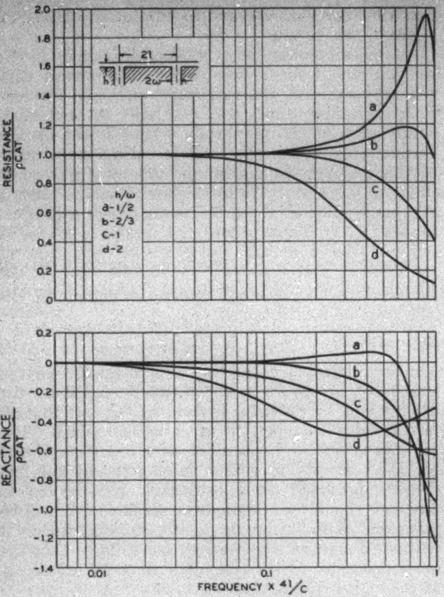


Fig. 6. Load impedance of speaker diaphragm

a region to be defined by a certain solid angle, it is necessary and sufficient that the radial motion be the same in amplitude and phase over the part of a spherical surface intercepted by the angle and having its center of curvature at the vertex and located at a sufficient distance from the vertex to make its dimensions large compared with the wave length. If, further, these conditions are satisfied for this surface at all frequencies, all points lying within the solid angle will receive sound of the same wave form. A horn was designed to meet these requirements for the high frequency band.

The horn, shown in the upper part of Fig. 5, comprises several separate channels, each of which has substantially an exponential taper. Toward the narrow ends these channels are brought together with their axes parallel, and are terminated into a single tapered tube which at its other end connects to the receiver unit. Sound from the latter is transmitted along the single tube as a plane wave and is divided equally among the several channels. If the channels have the same taper, the speed of propagation of sound in them is the same. The large ends are so proportioned and placed that the particle motion of the air will be in phase and equal over the mouth of the horn. This design gives a true spherical wave front at the mouth of the horn at all frequencies for which the transverse dimensions of the mouth opening are a large fraction of a wave length.

As the frequency is increased, the ratio of wave length to transverse width of the channels becomes less, and the sound will be confined more and more to the immediate neighborhood of the axis of each channel. The sound then will not be distributed uniformly over the mouth opening of the horn, but each channel will act as an independent horn. To have a true spherical wave front up to the highest frequencies, the horn would have to be divided into a sufficient number of channels to make the transverse dimension of each channel small compared with the wave length up to the highest frequencies. If it is desired to transmit up to 15,000 cps, it is not very practical to subdivide the horn to that extent. Both the cost of construction and the losses in the horn would be high if designed to transmit also frequencies as low as 200 cps, as is the case under consideration. However, it is not important that at very high frequencies a spherical wave front be established over the whole mouth of the horn. For this frequency region it is perfectly satisfactory to have each channel act as an independent horn, provided that the construction of the horn is such that the direction of the sound waves coming from the channels is normal to the spherical wave front.

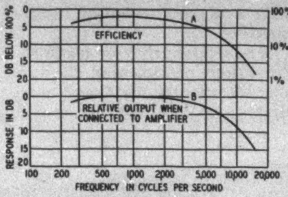


Fig. 7. Relative computed sound output of high frequency receiver

The angle through which sound is projected by this horn is about 60 deg, both in the vertical and in the horizontal direction. For reproducing the orchestra 2 of these horns, each with a receiving unit, were used. They were arranged so that a horizontal angle of 120 deg and a vertical angle of 60 deg were covered. These angular extensions were sufficient to cover most of the seats in the hall with the loud speaker on the stage. The vertical angle determines to a large extent the ratio of the direct to the indirect sound transmitted to the audience. The vertical angle of 60 deg was chosen purely on the basis of judgment as to what this ratio should be for the most pleasing results.

THE HIGH FREQUENCY RECEIVING UNIT

In the design of the low frequency receiver one of the main objectives was to reduce to a minimum the variations in sound transmission resulting from variations in the throat impedance of the horn. However, the high frequency horn readily can be made of a size such that the throat resistance has relatively small variations within the transmitting region. On the other hand, whereas the diameter of the diaphragm of the low frequency unit is only a small fraction of the wave length, that of the high frequency unit must be several wave lengths at the higher frequencies in order to be capable of generating the desired amount of sound. Unless special provisions are made there will be a loss in efficiency because of differences in phase of the sound passing to the horn from various parts of the diaphragm. The high frequency receiver therefore was constructed so that the sound generated by the diaphragm passes through several annular channels. There are enough of these channels to make the distance from any part of the diaphragm to the nearest channel a small fraction of a wave length. These channels are so proportioned that the sound waves coming through them have an amplitude and phase relation such that a substantially plane wave is formed at the throat of the horn.

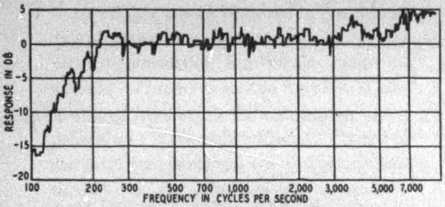


Fig. 8. Output-frequency characteristic of high frequency receiver as measured in a small room

In the appendix it is shown that, for the higher frequencies where the impedance of the horn may be taken as equal to ρc times the throat area and for the type of structure adopted, the radiation resistance is equal to

$$\rho c a T^2 \left[\frac{1}{k^2h^2T^2 + k^2l^2 \cot^2 kl}\right] \tag{6}$$

and the reactance

$$-j\frac{\rho c a}{kh}T\left[1 - \frac{1}{kl \cot kl + \left(\frac{hT}{l}\right)^2 kl \tan kl}\right] \tag{7}$$

where a is the area of the throat of the horn, T the ratio of the area of the diaphragm to the throat area, $k = \frac{\omega}{c}$, and the other designations are those indicated in Fig. 11. At the lower frequencies the resistance is T^2r and the reactance T^2x where r and x are, respectively, the resistance and reactance of the throat of the horn.

Equation 6 shows that at a given frequency, other conditions remaining the same, the radiation resistance will have a maximum value when l is approximately equal to $\frac{\pi}{2k} = \frac{c}{4f}$. In Fig. 6 the resistances as computed from eq 6 are plotted as a function of frequency for several values of $\frac{h}{w}$. It is seen from these curves that the resistance at the higher frequencies is determined very largely by the relation of $\frac{h}{w}$ but is independent of it at the lower frequencies, where it is equal to $\rho c a T^2$. At the lower frequencies where the mechanical impedance of the diaphragm is negligible, the efficiency, as was the case for the low frequency receiver, depends upon the value of B^2v where v is the volume of the coil, but at the higher frequencies the efficiency decreases with increasing mass of the coil. It is advantageous, therefore, to keep v small and to make B as large as is practically possible. Values were selected to give the receiver an efficiency of 55 per cent at the lower frequencies. For these conditions the relative sound power output was computed by eq 2 on the assumption that the receiver was connected to an amplifier having an output impedance equal to 0.45 times that of the receiver at the lower frequencies. Figure 7 shows the values so obtained. Corresponding values obtained experimentally when the receiver was connected to the horn previously described are shown in Figs. 8 and 9, where the sizes of the rooms in which the values were obtained were, respectively, 5,000 and 100,000 cu ft. Both of these curves differ considerably from the computed curve, particularly as regards loss at high frequencies. The curve of Fig. 8 shows less, and that of Fig. 9 more, loss at high frequencies. The computed curve, however, refers to the total sound output, whereas the measured curves give average values of sound intensity in a certain part of the room, values dependent upon the acoustic characteristics of the room.

Fig. 9. Output-frequency characteristic of combined low and high frequency receivers as measured in a large room

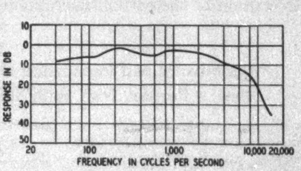
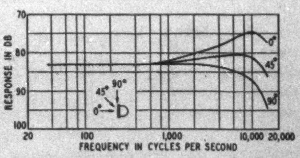


Fig. 10. Output-frequency characteristic of moving coil microphone



The number of high frequency receivers that must be used for each transmitting channel is governed largely by the amount of power that the system is to deliver before harmonics of an objectionable intensity are introduced. The generation of harmonics in a horn when transmitting waves of large amplitude already has been discussed. Let it suffice here to say that, for a given percentage harmonic distortion, the power that can be transmitted through the horn is proportional to the area of the throat and inversely proportional to the square of the ratio of the frequency to the cut-off frequency.

Inasmuch as the moving coil microphones used for the transmission of music in acoustic perspective have been described previously[8] they will not be discussed here at length. Their frequency response characteristic as measured in an open sound field for several different angles of incidence of the sound wave on the diaphragm are shown in Fig. 10 where it is seen that the response at the higher frequencies becomes less as the angle of incidence is increased. In general, this is not a desirable property, but with the instruments as used in this experiment the sound observed as coming from each loud speaker is mainly that which is picked up directly in front of each microphone; sound waves incident at a large angle do not contribute much.

At certain times the sound delivered by the orchestra is of very low intensity. Therefore it is important that the microphones have a sensitivity as great as possible, so that the resistance and amplifier noises may readily be kept down to a relatively low value. At 1,000 cps these microphones, without an amplifier, will deliver to a transmission line 0.05 microwatt when actuated by a sound wave having an intensity of 1 microwatt per sq cm. This sensitivity is believed to be greater than that of microphones of other types having comparable frequency response characteristics, with the possible exception of the carbon microphone.

Appendix—Load Impedance of a Diaphragm Near a Parallel Wall With Slot Openings

First assume a diaphragm and a parallel wall of infinite extent separated by a distance h, and that the wall is slotted by a series of equally spaced openings as shown in Fig. 11. From symmetry it is known that when the diaphragm vibrates there will be no flow perpendicular to the plane of the paper or across the planes indicated by the dotted lines. Therefore only one portion of unit width, such as *abcdef* need be considered. Let the x and y reference axes be located as shown. If the general field equation

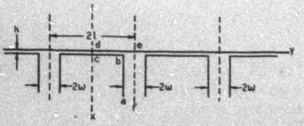


Fig. 11. Schematic diagram of diaphragm and parallel slotted wall of infinite length

$$\frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial y^2} + k^2\varphi = \xi \qquad (8)$$

is applied when the diaphragm has a normal velocity equal $\xi e^{i\omega t}$ the following boundary conditions are obtained:

When $x = 0, \quad \frac{\partial\varphi}{\partial x} = -\dot{\xi}$

$x = h, \quad \frac{\partial\varphi}{\partial x} = 0$

$y = 0, \quad \frac{\partial\varphi}{\partial y} = 0$

and when $y = l$, the pressure is equal to the product of acoustic impedance and volume velocity or

$$\frac{\rho}{h}\int_0^h \left(\frac{\partial\varphi}{dt}\right)_{y=1} dx = \frac{c\rho}{w}\int_0^h \left(\frac{\partial\varphi}{\partial y}\right)_{y=l} dx$$

where φ is the velocity potential, $k = \frac{\omega}{c}$, and c is the velocity of sound.

The appropriate solution of eq 8 then is

$$\varphi = \frac{\dot{\xi}}{k}\left[\frac{\cos ky}{kh\left(\cos kl + i\frac{h}{w}\sin kl\right)} - \frac{\cos k(x-h)}{\sin kh}\right]$$

The average reacting force per unit area of the diaphragm is

$$\frac{ik\rho c}{l}\int_0^l (\varphi)_{x=0}\, dy$$

Thus, for the impedance per unit area, which is equal to the force divided by the velocity, is obtained

$$\frac{\rho cl}{w}\left\{\left[\frac{\sin^2 kl}{k^2 l^2}\frac{1}{\cos^2 kl + \left(\frac{h}{w}\right)^2 \sin^2 kl}\right]\right.$$

$$\left. - j\frac{w}{h}\left[\frac{\cancel{\frac{kh\cos kh}{\sin kh}}\, kl - \frac{\sin kl\cos kl}{\cos^2 kl + \left(\frac{h}{w}\right)^2\sin^2 kl}}{k^2 l^2}\right]\right\} \equiv r' + jx'$$

In all practical types of loud speakers $\frac{kh\cos kh}{\sin kh}$ would be very nearly equal to 1; then

$$r' = \frac{\rho cl}{w}\left[\frac{1}{k^2 l^2\left(\left(\frac{h}{w}\right)^2 + \cot^2 kl\right)}\right]$$

$$x' = -\frac{\rho cl}{h}\left[\frac{kl - \frac{1}{\cot kl + \left(\frac{h}{w}\right)^2\tan kl}}{k^2 l^2}\right]$$

If the total area of the diaphragm is A and that of the corresponding channels a, then $\frac{A}{a} = \frac{1}{w}$, approximately, and the total impedance becomes

$$= \frac{\rho c A^2}{a}\cdot\frac{1}{\left(\frac{kh}{a}\right)^2 A^2 + k^2 l^2\cot^2 kl}$$

$$x = -j\frac{\rho c A}{kh}\left[1 - \frac{1}{kl\cot kl + \left(\frac{h}{l}\frac{A}{a}\right)^2 kl\tan kl}\right]$$

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Auditory Perspective —Amplifiers

Appreciable care is required in the design of a system which must amplify with great fidelity practically the whole range of audible frequencies and be capable of delivering a high level while at the same time providing a wide volume range. Some of the problems involved are discussed, particularly as applying to the equipment used in the reproduction in Washington, D. C., of the Philadelphia Symphony Orchestra playing in Philadelphia. This is the fourth paper in this symposium.

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VACUUM TUBE AMPLIFIERS have been closely identified with the extension of the channels of communication since, with completion of the initial transcontinental telephone line 20 years ago, they first enabled New York to converse with San Francisco. There are now thousands of audio frequency amplifiers in telephone circuits and in sound picture theaters, public address systems, and other similar services as well as in the millions of radio receiving sets.

Along with the extension of the field of usefulness of audio amplifiers there has been continuing progress toward more faithful reproduction, better transmitters, better receivers, and better amplifiers. Those first telephone repeaters, although quite adequate for their immediate purpose, transmitted a frequency band only a few octaves wide. Very few radio sets even now cover a range above 3,000 cps without distortion, and the most up-to-date sound picture installation rarely can be depended upon for accurate reproduction of frequencies above 7,000 or 8,000 cps. The requirements as to frequency range and freedom from distortion for any particular service are, in the last analysis, determined by public demand.

However, when one undertakes to reproduce an orchestra like the Philadelphia Symphony and to reproduce it in such a manner as to satisfy the critical ear of the director, or that of the devotee of symphonic concerts, one has to provide something out of the ordinary in audio amplifiers.

In his paper, which forms a part of this symposium, Dr. Fletcher has pointed out that "only the elimination of those frequencies below 40 cps and those above 15,000 cps produces no detectable difference in the reproduction of symphonic music." This, then, is the frequency spectrum that the amplifier must be designed to handle. Also, it is important that there shall be uniform amplification of all parts of the frequency range and that no extraneous frequencies shall be introduced.

Of importance commensurate with the distortionless amplification of the complete frequency range of the orcehstra is the provision of an equivalent volume of sound. The amplifier must be capable of supplying to the loud speakers without distortion an amount of energy that will produce a sound volume at least equivalent to that produced by the orchestra (the Philadelphia-Washington installation was designed to produce about 10 times this amount). And equally important, the amplifier must be so free from internal disturbances and from self-induced electrical fluctuations that the softest music, the weakest input to the microphone, can be reproduced without appreciable background noise. According to Fletcher the ratio of the heaviest playing of a large orchestra such as the Philadelphia Symphony Orchestra to the softest music such as that of a violin is about 10,000,000 to 1, or 70 db. Thus it is required that any noise be at least 75 db below the loudest tones; that is, there must be at least a 75-db volume range.

The sources of noise may be divided into 2 groups. In the first group are included the 60-cycle alternating current power supply, vibration or jar of mechanically unstable vacuum tubes, contact and thermoelectric potentials, and similar disturbances, which may be reduced to practically any degree depending upon the lengths to which one is willing to go to reduce them. In the second group are those electronic irregularities intimately associated with the operation of the vacuum tube and which depend somewhat upon the design, manufacture, and method of operation of the vacuum tube; and which, when sufficiently amplified and fed into a loud speaker, may be heard as noise. In general, the maximum volume range of an amplifier is reached when all other disturbances are reduced to the level of this tube noise.

It is evident, then, that under ordinary circumstances the limiting volume range of an amplifier is a function of the amount of amplification following the first tube. In other words, the magnitude of the signal voltage with respect to the noise voltage in the plate circuit of the first tube in a multistage amplifier determines the limiting volume range obtainable with that amplifier.

It will appear that in a sound reproduction system a highly efficient microphone simplifies the amplifier volume range requirements, and that loud speakers of high efficiency reduce the volume required from the amplifier.

Perhaps it is in order to inquire as to what makes an amplifier free from frequency distortion over a

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wide range. The answer might well be: attention to impedance relations. A compact, efficient amplifier requires several pieces of reactive apparatus such as transformers, retardation coils, and capacitors. One must remember that an inductance of one henry is equivalent to an impedance of 250 ohms at 40 cps but that it is nearly 100,000 ohms at 15,000 cps; that the grid circuit of the vacuum tube is not actually an open circuit even though the grid is maintained negative with respect to the cathode, but has a reactance which becomes important at high frequencies or with large ratio input transformers. Many years of development in this field have advanced the art to the point where transformers transmitting extremely wide bands now can be designed. The commercial production of such designs requires rigid inspection including shop transmission measurements under the actual conditions of use. The transformer must be designed for the particular type of vacuum tube with which it is to be used. First, however, the tube must be designed to permit its use under the proposed conditions and then it must be manufactured to close limits, every tube of a type like every other tube of that type.

This is, then, the general requirement for a wide frequency range amplifier: (1) attention to impedance relations; (2) meticulous design of each component for the particular job it has to do, and rigid inspection to insure that it does that job.

One might suppose that when the tube designer and the coil designer each had done his part the job was done. Such is not the case. The various pieces of apparatus have to be gathered together into a unit (often a current supply set for supplying anode, cathode, and grid potential is assembled with the amplifier) and out of this electrical and physical association is apt to arise "feed-back" and "noise."

When there is coupling between 2 parts of the amplification circuit which are at different potential or different phase there is feed-back. Feed-back sometimes is employed designedly to modify an amplifier characteristic, but, feed-back which may arise as a result of a particular arrangement of apparatus or wiring ordinarily will cause more or less severe frequency distortion. It may be induced due to stray electromagnetic or electrostatic fields, which must be eliminated by rearrangement of apparatus or by shielding; or it may be caused by common circuit impedance, requiring circuit modifications. In general, a low gain amplifier or one with limited frequency range presents no feed-back problems, but a study of a high-gain wide-range equipment usually is necessary in order to determine the best arrangement. Often modifications of tentative circuit or apparatus must be made to obtain satisfactory operation.

The provision of a volume range of some 75 db on an energy basis became largely a matter of the suppression of a-c hum. The low inherent electronic noise effect of the Western Electric No. 262A vacuum tube and the relatively high level from the microphones kept electronic tube noise well in the background. Careful and in some cases rather elaborate shielding of audio transformers and leads and the segregation of the 60-cycle power equipment coupled with the use of vacuum tubes having indirectly heated cathodes and specially designed to have small stray fields prevented a-c hum trouble in the early stages. However, the Western Electric No. 242A vacuum tubes used in the push-pull final

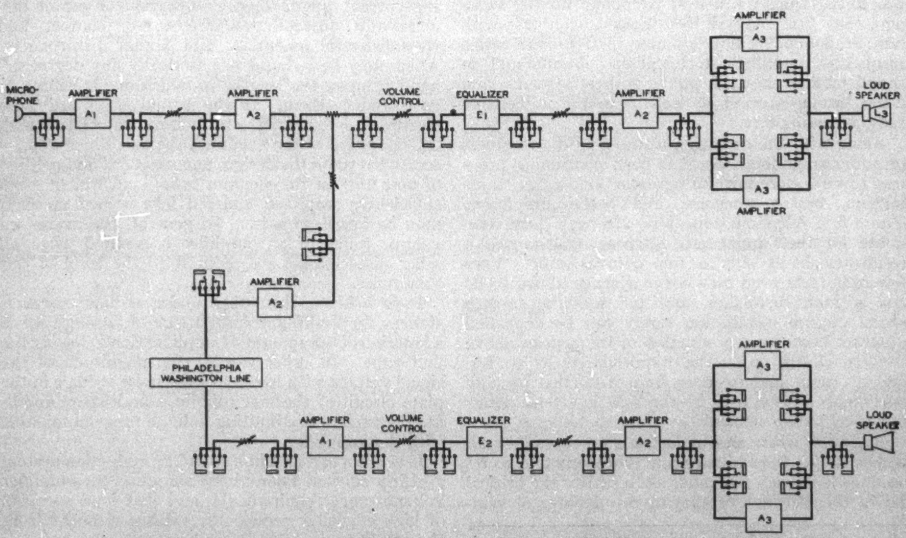

Fig. 1. Schematic diagram of the amplification system used in conveying Philadelphia symphonic music to Constitution Hall in Washington, D. C., and there reproducing it in auditory perspective

stage have filamentary cathodes, and when such tubes have raw a-c filament supply, a very appreciable 120-cycle component appears in the space current. Although theoretically in a perfectly balanced push-pull amplifier this component would be eliminated, in practice an exact balance cannot be obtained. As a final step in noise elimination, advantage was taken of the fact that each channel employed 2 amplifiers in parallel. Under such conditions and with proper phasing of the power supply to the 2 amplifiers the net a-c noise output of the 2 amplifiers in parallel will be less than that of either one alone.

Having reduced feed-back and noise to tolerable values, it remains to determine the operating conditions for maximum output. The vacuum tube is not strictly a linear device, but, when properly used, the total harmonic content can be held to a low figure. For a high quality system the total harmonics produced in the system should not exceed one per cent of the fundamental. This requires that impedance and potential relations in the vacuum tubes should be adjusted to give approximately linear operation; and also that the design of audio transformers, particularly those carrying considerable levels, must be scrutinized carefully to insure that they operate over an essentially linear portion of the magnetization curve of the core material.

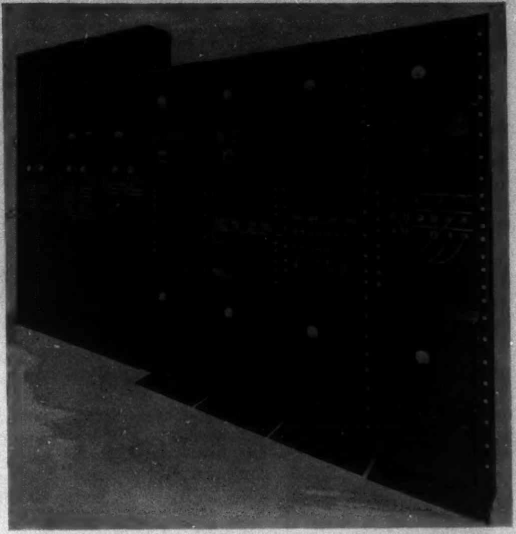

Fig. 2. Amplifying equipment used at Philadelphia. The taller racks are 8 ft high and contain A_1 and A_2 amplifiers, volume indicators, and various controls

An instrument really essential to the design of high quality amplifiers is a high sensitivity harmonic analyzer that is capable of quickly and accurately resolving a complex wave into its simple components. By this means the effect of variations in circuit relations can be evaluated and the optimum condition for maximum distortionless power output determined.

It may be desirable at this point to examine the make-up of the audio amplification system used in the Philadelphia-Washington experiments. It should be noted that the arrangement of equipment provided for simultaneous reproduction at both Philadelphia and Washington. There were 3 complete and essentially equivalent channels of equipment actually in use and a fourth complete channel held in reserve as a spare.

Several stages of so-called voltage amplification were required preliminary to the final or power stage. There is, of course, no essential difference between a voltage amplifier and a power amplifier, the term "voltage amplifier" being applied to those preliminary stages of an amplification system the function of which is so to amplify the output of the pick-up device as to supply adequate driving voltage to the grids of the power stage. Theoretically, inasmuch as no energy is absorbed in the ideal grid circuit, this voltage increase might be supplied entirely by a high ratio input transformer. However, there are practical difficulties to the design of such a single stage amplifier and therefore multistage vacuum tube amplification is employed.

As a matter of convenience the voltage amplification for this system was obtained through the use of several separate amplifier units in tandem. This arrangement not only enabled the ready replacement of any unit of the system in case of failure, but it also facilitated the insertion of a pad, control potentiometer, or other network at any desired point. Several of these devices were required, and of course each introduced a loss. Thus the gross amplification of the system used for reproduction at Philadelphia was approximately 160 db and for Washington 240 db, although the actual difference in level between microphone output and loud speaker input was but from 80 to 90 db.

The general scheme of the amplification system is shown in Fig. 1. A_1 is a single-stage, single-tube Western Electric No. 80A amplifier slightly modified to meet the particular conditions of use; it has a gain of 30 db, and employs a Western Electric No. 262A vacuum tube. This tube has an equipotential cathode, the heater being operated on 10-volt 60-cycle alternating current and the anode being supplied from rectified alternating current. A_2 is a 2-stage amplifier having a single Western Electric No. 262A vacuum tube in the first stage and push-pull Western Electric No. 272A tubes in the second stage. It has a gain of 50 db. The cathodes of the tubes are energized with low-voltage 60-cycle alternating current and the anodes with rectified alternating current. A_3, the final or power amplifier, is a single stage amplifier employing 2 Western Electric No. 242A vacuum tubes in parallel on each side of a push-pull circuit, thus having 4 tubes per amplifier.

Two of the A_3 amplifiers were used in parallel on each channel, and were capable of supplying 60 watts each, or a total of 120 watts, to the loud speakers. These are rms values. The instantaneous peaks of power of course could equal twice this value, or 720 watts, for the 3 channels. E_1 and E_2 are equalizers to compensate for any amplitude distortion that would cause a listener to obtain a different tone effect from the loud speakers than he would from the actual orchestra. These equalizers are loss networks and principally equalize for the acoustic characteristic of the loud speakers in the particular hall, but they are placed in a low energy part of the amplification circuit so as not to waste the energy of the final power stage.

In view of the inclusion of the equalizers in the amplification system, and particularly because of the fact that the amplification of the A_3 amplifier deliberately was made to increase with frequency in order to compensate in part for acoustic losses in the overall system, the actual amplification-frequency curves of the amplifiers are of little importance. The equalizers of the system are discussed in a paper by Bedell and Kerney. (See page 216.)

Auditory Perspective —Transmission Lines

Describing methods whereby high quality sound reproduction in auditory perspective can be accomplished over long distances, this discussion centers largely upon a description of the exact technique employed in providing communication transmission circuits for the Philadelphia-Washington demonstration. Problems that might be involved in carrying out such transmission on a more widespread scale also are touched upon. This is the fifth paper in this symposium.

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MICROPHONES have been described that will pick up without noticeable distortion all the sounds given forth by a symphony orchestra. Loud speakers and amplifiers also have been described that will accurately reproduce this highest quality music in its full range of tone quality and volume. Therefore, the situation obviously requires connecting transmission paths so perfect in their characteristics that reproduction 100 or 200 miles away may not suffer in comparison with reproduction which may be only 100 or 200 ft from the source of music.

There are several respects in which a long line circuit possibly may distort the speech or music passed over it, unless considerable effort is expended to overcome these tendencies. For example, there may be frequency-amplitude distortion; i. e., all the notes and overtones may not be transmitted with the proper relative volumes. Similarly there may be phase or delay distortion, the different frequencies may not arrive at the receiving end of the line circuit in the same time relationships in which they originated. A line circuit is subject also to possible inductive disturbances from other communication circuits ("crosstalk"), or from power or miscellaneous circuits which cause "noise" at the receiving terminal. If the circuit contains amplifiers, transformers, and inductances having magnetic cores, it is subject to possible nonlinearity effects; i. e., the current at the receiving end of the line may not follow exactly the amplitude variations of the current applied to the transmitting end or, what is more important, spurious intermodulation frequencies may be generated within the transmission circuit and mar the purity of the musical tones. The problem of reproduction in auditory perspective, using 2 or 3 paralleling channels, also adds the requirement that these channels must be substantially identical in their transmission characteristics.

With the exception of the last, all these aspects of the problem are, of course, not peculiar to symphony music transmission. They exist as part of the problem of satisfactorily transmitting any telephone message. However, the requirements of this new high quality transmission have set a new high standard of refinement, even as compared with that required for ordinary radio chain broadcasting. For example, ordinary telephone message transmission commonly is carried out by circuits having a frequency range not exceeding 200 to 3,000 cycles per second. Much present-day radio broadcasting involves a transmission band only from about 100 to 5,000 cps. This new high quality transmission,

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however, requires a range from approximately 40 to 15,000 cps. Further, with reference to the required freedom from interference, ordinary radio broadcasting seldom exceeds a volume range greater than 30 decibels. The new high-quality system, however, requires a volume range of at least 65 db, which is more than 3,000,000 to 1 expressed as a power ratio.

In considering the specific problem of transmitting from Philadelphia to Washington for the demonstration given on April 27, 1933, several alternative methods of providing the required transmission paths presented themselves. The arrangement chosen consisted in bridging the distance between the 2 cities by means of carrier channels over cable conductors. From the telephone toll office in Philadelphia to the toll office in Washington, 3 carrier transmission paths were provided in which the music frequencies were stepped up from their normal position in the audible range to considerably higher frequencies. The frequency range from 40 to 15,000 cps picked up by the microphones was transmitted over line circuits in a range from 25,000 to 40,000 cps. After being thus stepped up in frequency, the high frequency currents were applied to 3 nonloaded pairs in an all-underground cable which was equipped with repeaters at approximately 25-mile intervals. At Washington, step-down or demodulation apparatus restored the frequencies to their normal position in the spectrum.

For transmission between the auditorium in Philadelphia and the toll office there, a distance of approximately 3 miles, and for transmission in Washington between the telephone toll office and the auditorium, about half this distance, normal frequency transmission over small-gauge pairs in ordinary exchange cables was employed.

The use of the carrier method for the long distance transmission has several advantages. In general, it permits multiplex operation; i. e., more than one message or program on the same pair of wires. As a matter of expediency in this particular case this feature of operation was not used, and 3 separate pairs were employed, one for each channel. In the future the same technique undoubtedly would permit 2 or possibly more of these extra-broad-band transmission paths to be obtained on the same pair of conductors. The most important reason for choosing the carrier method rather than transmission in the natural audio-frequency range in this particular case was that, because all other transmission circuits in the same cable were at a considerably lower frequency and because the lead sheath of the cable acts efficiently at the high frequencies to shield the pairs from induced disturbances from the outside, it offered a special freedom from crosstalk and noise.

With these arrangements, which will be described in somewhat greater detail in what follows, requirements of transmission were met very satisfactorily and the reproduction of the symphony music in Washington with the orchestra playing in Philadelphia suffered not the least in comparison wiht the reproduction of the same program in an auditorium in Philadelphia located but a few feet from the hall in which the orchestra played. It is believed that, if necessary, by the use of the same principles, line circuits may be set up and comparable quality reproduction given throughout the country. However, as will be evident from part of the discussion which follows, in some respects the problem of meeting the requirements in transmission between Philadelphia and Washington was not as difficult as might be encountered in other localities. Hence even more complex arrangements might be necessary if it were desired to establish such transmission circuits to other points, and particularly for greater distances.

LINE CIRCUITS

There are several all-underground cables between Philadelphia and Washington. As described in a paper[1] by Clark and Green given before the A.I.E.E. in 1930, recently laid cables contain several 16-gauge conductors distributed throughout the cross section of the cable for possible use as program circuits in chain broadcasting. These pairs, however, ordinarily are loaded and equipped with repeaters at approximately 50-mile intervals so that they transmit a frequency range up to about 8,000 cps.

In one of the cables several pairs of this type had not yet been loaded, and these pairs were used for this newer transmission. Because of the higher frequencies employed and the greater attenuation encountered, it was necessary to install repeaters at more frequent intervals. As may be noted in Fig. 1, the normal cable layout between Philadelphia and Washington includes 2 intermediate repeater stations, one at Elkton and one at Baltimore. Additional repeater stations were established accordingly at in-between points—Holly Oak, Abingdon, and Laurel. One of these repeater points, Holly Oak,

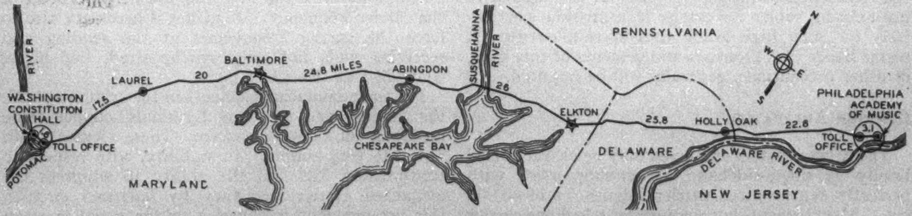
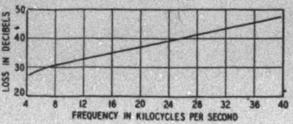


Fig. 1. Geographical layout of 3-circuit communication line used to carry Philadelphia symphony music to Washington, D. C., for reproduction in auditory perspective

was established in a local telephone office. No such convenient housing existed at the other 2 points, and it was necessary to establish new repeater stations. These were small metal structures large enough to house only the repeaters, their power supply, and testing equipment. This apparatus was arranged to be normally nonattended, various switching actions being remotely controlled from the nearest regular repeater station.

Fig. 2. Line attenuation characteristic of typical repeater section



The line attenuation between repeater points is shown in Fig. 2. It may be noted that the attenuation is approximately 50 db for the highest carrier frequency involved. A diagram showing the variations in power level as the carrier waves traverse the complete circuit is shown in Fig. 3. Because of the variation in attenuation over the frequency range employed it was necessary, of course, to use equalizers at the input of each repeater; i. e., networks having an attenuation variation with frequency approximately the inverse of that of the line circuit.

NOISE

In setting up these circuits various tests, including measurements of noise currents picked up by the conductors to be employed, were made prior to the actual installation of the apparatus. It was discovered that on the cable circuits north of Baltimore these pairs were picking up sufficient noise even at the higher frequencies to constitute a possible limitation in the volume range that might be delivered. This noise was generated chiefly as a by-product of relay and other similar operations within the Baltimore office and was propagated over the longitudinal circuits of various pairs in the cable from which, by induction, it entered the special selected pairs. As a remedial measure, longitudinally acting choke coils applied to all but the specially selected pairs in the cable greatly reduced the noise. Shielding and physical separation were employed in the Baltimore office to prevent induction between the repeaters and the connection to the main cable. If it is desired to use existing cables for carrier transmission, particularly for such high grade transmission circuits, it seems likely that filtering arrangements of this kind, or other precautions, generally will be required.

CARRIER APPARATUS

The carrier system employed may be characterized briefly as single-sideband carrier-suppressed, with perfectly synchronized carrier frequencies of 40,000 cps. Most present-day commercial telephone carrier systems are of the single-sideband carrier-suppressed type. Suppressing one sideband saves frequency space and suppressing the carrier reduces the load on the line amplifiers or repeaters. Ordinarily the exact synchronization of the carrier frequencies at the sending and receiving ends is not required for message telephone service.

Obtaining a single sideband after modulation commonly is carried out by providing band filters which transmit the desired sideband and suppress the unwanted sideband. For the requirements of message telephone transmission this does not impose severe requirements in the design of filters because audio frequencies less than about 100–200 cps ordinarily are not transmitted, in which case, if the filter in suppressing the unwanted sideband tends to cut off the lower frequencies of the desired sideband, it is not important.

For the requirements of this new high quality system, however, where it was desired to transmit all frequencies to at least as low as 40 cps, the problem was considerably more difficult. Two alternatives presented themselves in the design of the required filters. The first consisted in attempting to provide the required selectivity in the filters themselves, perhaps supplementing the actions of inductance coils and condensers (which normally make up such a filter structure) by quartz crystals to provide the sharp selectivity required on the sides of the band. The other alternative consisted in providing a filter of moderate selectivity so that in the neighborhood of the carrier frequency the unwanted sideband is not completely suppressed, and in arranging that the resultant reproduced music at the receiving terminal is obtained by the proper coördination of the desired and the vestige of the unwanted sideband. The "vestigial" sideband method was decided upon. Although this does not require filters having particularly sharp selectivity on the sides of the band, it does, however, impose more severe requirements upon the control of the phase characteristics of the filters in the neighborhood of the carrier frequency. It makes it necessary also to have the carrier frequencies at the sending and receiving ends not only synchronized, but phase controlled as described later.

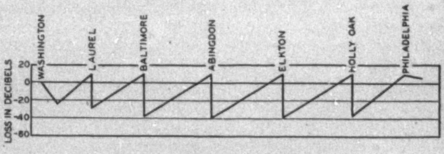


Fig. 3. Transmission level diagram

For the modulating elements in the system at both the sending and receiving terminals, copper oxide rectifying disks were chosen. These elements can be made very simple. In stability, with respect to transmission loss and the ability to suppress the unwanted carrier frequency by balanced circuits, this arrangement is superior to the usual vacuum tube circuits.

In Fig. 4 is shown schematically the arrangements of the carrier circuit at the transmitting and receiving ends. At the transmitting terminal the circuit from the microphones is led first through low- and high-pass filters to limit the bands to the desired width; i. e., 40 cps to 15,000 cps. The 40-cycle limiting filter was included because tests had demonstrated that lower frequencies are not required for the satisfactory transmission of music of symphony character, and because it was feared that occasional high energy pulses of subaudible frequency might cause overloading. When these 40-cycle filters are omitted, as was done in tests, the carrier channels are capable of transmitting frequencies down to and including zero frequency, a characteristic which could not possibly be obtained in a single sideband system by other than such a vestigial sideband technique.

As may be noted further in Fig. 4, carrier current is supplied to the rectifying disks of the modulator along with the incoming music frequencies. The balancing connection of the 4 rectifying disks making up the modulator is arranged to suppress the carrier frequency, the final degree of suppression being adjusted by means of the variable condenser and resistance shown, which were included to make up for slight dissimilarities in the characteristics of the individual copper disks. A very high degree of carrier suppression can be achieved by this means. No difficulty was experienced in maintaining a ratio of at least 60 db between the carrier voltage applied to the unit and the residual carrier current not completely balanced out. Over short periods an even higher degree of balance can be readily obtained.

There is a certain amount of electrical noise generated in the rectifying disks over and above that caused by thermal agitation[2,3] effects. The amount of this noise compared with the maximum permissible modulation output determines the volume range possibilities of a modulator of this type. Measurements indicated that this range was approximately 90 db, which obviously was more than sufficient to meet the requirements desired.

The circuit includes a relay and a meter through both of which flows the d-c component produced by the rectification of the carrier frequency. These supplementary units give a check on the magnitude of the carrier supply and afford an alarm in case of failure. From the modulator unit the circuit is connected to the band filter which transmits only the lower sideband lying between approximately 25,000 and 40,000 cps and the vestige of the upper sideband. From the band filter the currents are led to an amplifier and thence to the line circuit leading to the farther terminal.

It may be noted that at the transmitting terminal the 40,000-cycle carrier current is derived from a 20,000-cycle oscillator by passing its output through a series of copper oxide rectifiers connected to form a frequency doubler. Part of the originally generated 20,000 cycles also is connected to the input of the transmitting amplifier and sent over the line to be used in producing the 40,000-cycle carrier supply for demodulation.

At the receiving terminal a similar modulation or demodulation process occurs through the use of copper oxide disk circuits. A relay and meter also are included in the circuit to check the carrier supply,

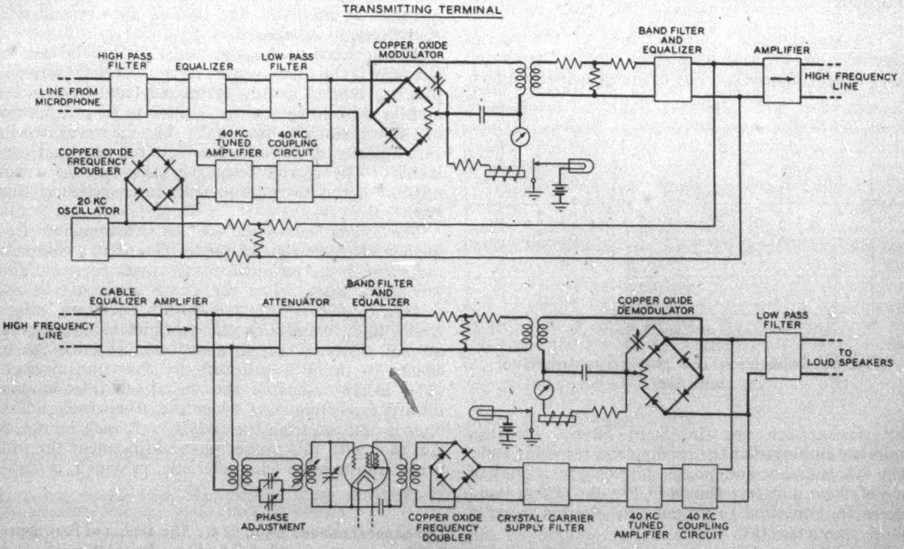

TRANSMITTING TERMINAL
HIGH PASS FILTER
EQUALIZER
LOW PASS FILTER
COPPER OXIDE MODULATOR
BAND FILTER AND EQUALIZER
AMPLIFIER
LINE FROM MICROPHONE
HIGH FREQUENCY LINE
COPPER OXIDE FREQUENCY DOUBLER
40 KC TUNED AMPLIFIER
40 KC COUPLING CIRCUIT
20 KC OSCILLATOR
CABLE EQUALIZER
AMPLIFIER
ATTENUATOR
BAND FILTER AND EQUALIZER
COPPER OXIDE DEMODULATOR
LOW PASS FILTER
HIGH FREQUENCY LINE
TO LOUD SPEAKERS
PHASE ADJUSTMENT
COPPER OXIDE FREQUENCY DOUBLER
CRYSTAL CARRIER SUPPLY FILTER
40 KC TUNED AMPLIFIER
40 KC COUPLING CIRCUIT
RECEIVING TERMINAL

Fig. 4. Schematic diagram of carrier terminal circuits

in this case providing also a check or pilot of the transmission over the long line circuit. The 20,000-cycle synchronizing current is selected at the receiving terminal, amplified and applied to a frequency doubler, and thence applied to the demodulator circuit. The input of this carrier supply circuit includes also a phase adjusting variable condenser arrangement so that the phase of the carrier supplied to the demodulator may be adjusted properly in relation to that of the carrier supplied to the modulator at the sending end. An interesting feature of the receiving terminal carrier supply is the quartz crystal filter employed to select the 40,000-cycle carrier after frequency doubling. The transmission characteristic of this extremely selective filter is shown in Fig. 5.

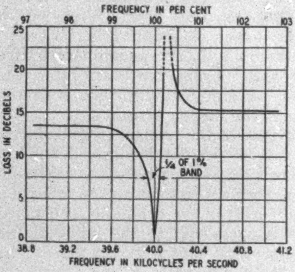


Fig. 5. Transmission characteristic of carrier supply crystal filter

FILTERS

The transmission characteristics of the carrier channels are determined largely by the filters and associated equalizers. The filters principally affecting transmission are the band filters. Identical units are employed at the sending and receiving ends. The transmission and phase shift characteristics of one of these units are shown in Fig. 6. These band filters are equalized to produce the desired squared band characteristic.

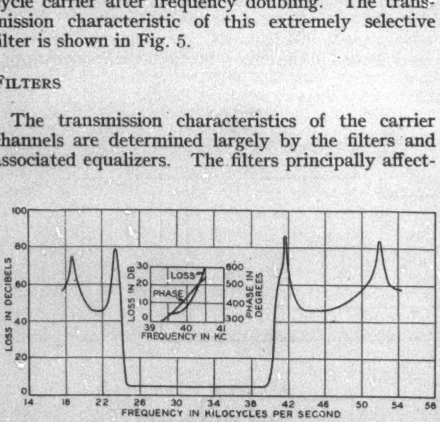


Fig. 6. Transmission and phase characteristics of band filter

The characteristics in the frequency region near the carrier (i. e., at 40,000 cycles) are shown on a large scale. This region is of particular interest because it is here that the degree of success in the application of the vestigial sideband method, for the purpose of insuring the satisfactory transmission of the low music frequencies, is determined. If for a given frequency interval above the carrier the phase change is arranged to be equal and opposite to that of the same frequency interval below the carrier, then in the action of demodulation the demodulated current produced by the action of one sideband adds itself arithmetically to that produced by the other sideband. It will be noted that this desirable phase characteristic has been achieved closely in the characteristics shown. If, in addition, the attenuation loss in the filter is adjusted so that the sum of the regular and vestigial sideband amplitudes corresponding to the low music frequencies is substantially constant and equal to the amplitude of the frequencies at midband, the desired flat transmission characteristic is assured.

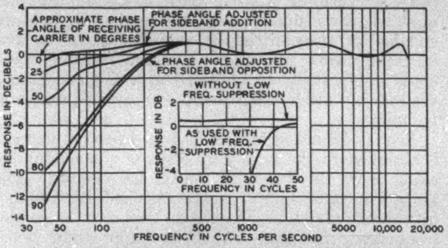


Fig. 7. Over-all transmission characteristics as a function of the phase relation of the receiving carrier

As was noted previously, this action can be carried out only if the phase angle of the receiving carrier is properly related to thht of the sideband frequencies and, in turn, to the carrier applied to the modulator at the transmitting terminal. The curves shown in Fig. 7 illustrate the influence that the phase adjustment of the carrier frequency has on the transmission of the lower frequencies in a system of this kind.

The upper curve shows the transmission frequency characteristic of one of the carrier channels measured from terminal to terminal between distortionless lines, when the phase angle of the receiving carrier is adjusted for its optimum value. Under these conditions the vestigial sideband and normal sideband supplement each other in their effects to produce substantially flat transmission. (The insert indicates the sustained transmission toward zero frequency when the 40-cycle highpass filter is omitted from the circuit.) It may be noted also that with this proper phase adjustment the full band transmission characteristic provided is sub-

This paper continued on p. 214. The sixth and final paper in this symposium entitled "Auditory Perspective—System Adaptation" follows the remainder of this paper, beginning on p. 216.

Lightning Measured on 4-Kv Overhead Circuits

For the past 4 years actual lightning potentials on the 4-kv overhead distribution system of the Commonwealth Edison Company, Chicago, have been measured by means of surge voltage recorders. The methods used and conclusions drawn from the results obtained are given here.

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THIS work seems unique in that direct measurements of the potentials of natural lightning surges impressed on the distribution system have been made. Heretofore A.I.E.E. papers on the magnitude of natural lightning potentials on overhead systems have been confined to the results of measurements on high voltage lines. The direct application of this high voltage data to the design of overhead distribution systems is neither simple nor accurate; consideration must be given, for example, to the different types of construction involved, to the effect of tap lines and of spacing of equipment, to length of circuits, and to relatively low impulse strength of distribution equipment. Furthermore, on the high voltage lines it usually is possible to have a full development of lightning surges into traveling waves, whereas on distribution circuits the waves develop to little or no extent.

It seemed therefore that an investigation of the lightning potentials occurring on an overhead distribution system should be of considerable value in the design of transformers and other overhead plant equipment, and in the design and application of lightning protective equipment. The present study supplements Roper's[1] statistical investigations of lightning protection on the Chicago system.

The principal conclusions to be drawn from the results of this investigation are:

1. Lightning voltages at transformers are reduced materially by the use of arresters.
2. Usually arresters on urban circuits must be capable of discharging successfully surge currents less than 300 amperes.
3. With the arrester ground and secondary neutral main interconnected, only the arrester potential appears between the primary coil and the secondary neutral main.
4. Known direct strokes had negative polarity and the maximum voltage was 488 kv.
5. Where there was no evidence of flashover, the voltages recorded on these distribution lines in open territory with little equipment were about 300 kv or less.
6. Voltages below the flashover value of the line insulation probably were induced surges, and for the higher voltages there was a preponderance of negative surges.
7. The probability that high lightning voltages may occur at transformer locations on "long" circuits is 10 or 20 times as great as that for urban circuits. The probability of direct strokes is remote.
8. For the long circuits, lightning voltages caused by a single cloud discharge seem to cover 1,000 to 3,000 ft of the line. Generally on urban circuits the voltages are restricted considerably more by the closely spaced arresters.
9. Usually in urban territory the maximum lightning voltages impressed are considerably less than 200 kv.
10. For lightning voltages of the same magnitude, the insulation of transformers having the interconnection is stressed considerably less than insulation of transformers having normal arrester protection.

Distribution System

The distribution plant[1] is a 4-wire, 3-phase, 2,300/4,000-volt system with the neutral grounded at the substation. All the circuits leave the substations via underground cables, and all the line transformers are single-phase. Arresters are installed on the primary wires only. One 3,000-volt and one 300-volt arrester are installed on the same pole with each lighting transformer, while on 3-transformer installations 3 3,000-volt arresters and 1 300-volt arrester are installed with the further limitation that the maximum number on transformers in 1 block is 3 3,000-volt and 1 300-volt arrester. Arresters are installed at cable poles on each primary wire extending from the pole; the distance between arresters on each phase wire generally is less than 1,000 ft. The resistance of over 97 per cent of the arrester grounds is 25 ohms or less; and of 0.3 per cent the resistance is above 50 ohms.

The terrain of Chicago is quite flat. The primary wires are about 28 ft above ground; the secondary mains usually are installed on a separate arm 2 ft below the primaries. The wire spacings and insulators used are standard for such circuits. The secondary neutral main is grounded to driven pipes and generally to several water pipes in customers' premises in each block. In about 85 per cent of the cases the secondary neutral mains of adjacent blocks are interconnected. The combined secondary grounds have a resistance of less than one ohm.

Method of Investigation

The surge voltage recorders used were of the stationary film type[2] and were developed by the General Electric Company for this investigation. The device consists essentially of a porcelain housing and removable container with 2 films that record direct and reversed polarity measurements of each surge. The instrument has a range of 2.5 to about

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Full text of a paper recommended for publication by the A.I.E.E. committee on protective devices, and scheduled for discussion at the A.I.E.E. winter convention Jan. 23–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Nov. 13, 1933. *Not published in pamphlet form.*

[1] For references see end of paper.

30 kv, and has a possible error of about 20 per cent. To record voltages above 30 kv, a capacitance voltage divider consisting of 1, 2, or 3 standard suspension insulator units was mounted rigidly on the top of the recorder, giving maximum voltages within the calibration range of the recorder of 150, 230, and 390 kv, respectively. Voltages somewhat higher could be estimated.

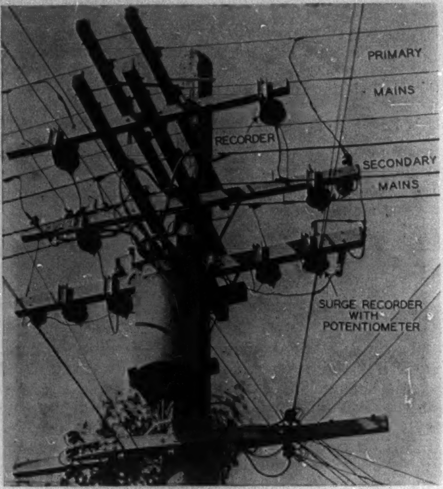
PRIMARY
MAINS
RECORDER
SECONDARY
MAINS
SURGE RECORDER
WITH
POTENTIOMETER

Fig. 1. Installation of 8 surge recorders on transformer pole. Voltages at transformer shown in Fig. 7 were obtained at a similar installation.

About 100 recorders were installed in various types of locations scattered over the city. Recorders were installed on ordinary line poles and on poles carrying transformers or cable terminals with various types of arresters. Eight recorders were installed on each of 8 transformer poles (Fig. 1) to obtain information on the magnitude of the impressed lightning surge and on its division among the various portions of the apparatus (Fig. 7).

To determine the magnitude of surge currents passing through distribution arresters, a special thyrite arrester with leads brought out from the terminals of the thyrite disk itself was installed on the first pole adjacent to each of these transformer poles, and a recorder was connected in parallel with the disk. The arrester was connected to a different primary phase wire than was the transformer.

Two recorders were installed on each of 8 cable poles. Two of these installations were made in the same blocks as those in which 8 recorders were installed on the transformer poles. In these 2 blocks a recorder also was connected between the open end of the primary mains and ground.

In order to obtain information on long primary lines to which little apparatus is connected—a condition that applies to a small portion of Chicago—recorders were connected every 400 ft of 1,600 ft of primary line at 2 different locations in open country (see Fig. 2).

Early in 1932 the Commonwealth Edison Company began to make interconnections of the ground side of lightning arresters with the secondary neutral mains. The data heretofore reported[3,4] on the benefit of interconnection have been obtained with artificial surges. In order to check these studies in the field, 2 recorders were installed at each of 12 locations having interconnections. These recorders are illustrated in Fig. 3.

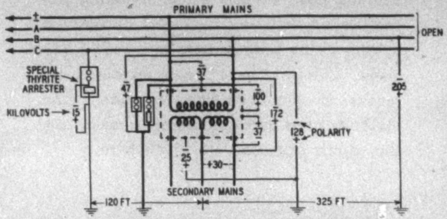
PRIMARY MAINS
±
A
B
C
OPEN
SPECIAL
THYRITE
ARRESTER
KILOVOLTS
15
47
37
100
172
37
128
POLARITY
205
25
+30
SECONDARY MAINS
120 FT
325 FT

Fig. 2. Installation of surge voltage recorders on 2 "long" circuits. Spacings between recorders are averages for the 2 locations studied

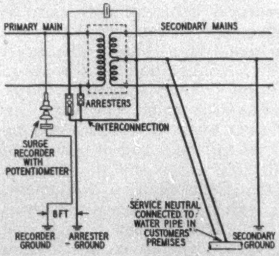
PRIMARY MAIN
SECONDARY MAINS
ARRESTERS
INTERCONNECTION
SURGE
RECORDER
WITH
POTENTIOMETER
8 FT
RECORDER
GROUND
ARRESTER
GROUND
SERVICE NEUTRAL
CONNECTED TO
WATER PIPE IN
CUSTOMERS'
PREMISES
SECONDARY
GROUND

Fig. 3. Surge voltage recorders at transformer with interconnection

In general, precautions were taken to obtain clearances in order that the effects of mutual coupling of adjacent connections might be kept to a minimum. The separate grounds for the recorders were all driven 8 ft or more from the arrester ground, and the 2 ground wires were installed on opposite sides of the pole to minimize their mutual effects. The ground resistances at the test locations were about 15 ohms.

Replacements of films were made after each storm which seemed sufficiently severe to make probable the obtaining of records. It was possible that several surges could be impressed upon the recorders during any one storm, but there were few cases of superposition of Lichtenberg figures on the films. After development of the films, the voltages indicated by the positive figures were estimated from a calibration curve, since the negative figure cannot accurately be calibrated. Information of trouble on the system due to lightning was correlated with the data furnished by the recorders.

SURGE VOLTAGES RECORDED

During the investigation, 1,883 pairs of films were developed, or an average of about 5 pairs of films per recorder per year; 311 voltages were recorded. (Tables I and II.)

Analysis shows (Fig. 4) for both urban and "long" circuits a preponderance of negative surges of high magnitudes. Some high negative voltages not associated with damage to poles or crossarms were measured. These may have been induced by the discharge of a positive cloud or, in some cases, may have resulted from streamers from negative direct strokes. This is in agreement with measurements on transmission lines where the highest voltages were predominantly negative.

Table I—General Statistical Data on Lightning on 4,000-Volt Circuits

Year	No. of Thunderstorms	Transformer Troubles Due to Lightning: No. of Fuse Blowings	Transformer Troubles Due to Lightning: No. of Burnouts	No. of Pairs of Surge Recorder Films Installed	No. of Records Obtained	Per Cent of Films Showing Records
1930	37	229	103	392	33	8.4
1931	46	234	92	464	86	18.5
1932	40	287	101	511	91	17.8
1933*	37	267	106	516	101	19.6
Total	160	1,017	402	1,883	311	16.5

* To November 1, 1933.
Note: Average number of transformers on overhead system in 1930 to 1933, inclusive, was 32,926.

Figure 5 shows that the probability of high lightning voltages on long exposed circuits with low arrester densities is 10 or 20 times that on urban circuits. Under Chicago conditions, for example, the probabilities of a transformer installation being subjected to a surge voltage of 50 kv during a thunderstorm are about 1.9 per cent for long circuits and about 0.15 per cent for urban circuits. Very high voltages are rare; Chicago data[1] indicating 1 transformer failure due to a direct stroke per 200,000 transformers per storm. Cases in which there was damage such as shattering of the pole or cross-arm or injury to near-by trees were considered as direct strokes.

"Long" Circuits. The highest voltage recorded was 488 kv, and this was obtained on a long circuit. There was evidence that a direct stroke or side flash had occurred on the pole on which the record was obtained. The adjacent recorders on each side indicated voltages of the order of 290 kv and 95 kv. An arrester was installed at the latter location. At the other long circuit location, 475 kv was recorded in another storm; again there was evidence of a direct stroke on the pole on which the record was obtained. A record of 277 kv was obtained in a case where there was evidence of flashover on several poles. It was unusual that 3 direct strokes or side flashes occurred at these locations in only 4 years. Voltages of slightly lesser magnitude have been recorded where no evidence of flashover has been found. Probably the maximum voltage which can exist on these circuits without flashover of the line insulation is of the order of 300 kv.

Also, these installations have furnished some interesting data on the spread of voltages over the line, and have given evidence that fully developed traveling waves do not exist on distribution circuits (Fig. 6). An impulse voltage caused by a single cloud discharge seems to cover approximately 1,000

Table II—Summary of Surge Voltages Recorded From 1930 to 1933, Inclusive

Surge Voltage Recorder Connection	Number of Installations	Number of Surges Recorded in Voltage Range (Kv) Shown: 3–10	11–25	26–50	51–100	101–150	151–200	201–250	251–300	301–350	Over 350	Total
Transformer Poles	8											
Primary phase to transformer case			8	1	2(100)							11
Primary phase to separate ground			3	5		1(128)						9
Primary phase to arrester ground		25	18	2(47)								45
Primary neutral to transformer case		49	4	2(45)								55
Primary phase to secondary neutral			11	2	1		1(172)					15
Secondary phase to transformer case		2	1	1	1(78)							5
Secondary phase to secondary neutral		1	1	2(37)								4
Transformer case to separate ground			2(25)									2
Special Thyrite Arrester	8											
In parallel with thyrite unit		31	1(15)									32
Cable Poles	8											
Primary phase to lead sheath of cable			3	2(33)								5
Primary phase to separate ground				1	1(78)							2
Long Circuits	2											
Primary phase to separate ground			4	16	14	10	8	7	6	8	3(488)	76
Open Primaries	2											
Primary phase to separate ground			3	1				1(205)				5
Interconnections (1932 and 1933 only)	12											
Across transformer		21	15(23)									36
Primary phase to separate ground			3		2		1(158)					6
Totals		130	76	35	21	11	10	8	6	8	3	308*

Figures in parentheses are highest voltages in kilovolts recorded.
* Does not include 3 records containing negative figures only, from which voltages could not be determined.

to 3,000 ft of line and the profiles of the voltages possibly resemble the distribution of bound charges.

It is to be noted that the lightning voltages at the poles with arresters did not exceed 148 kv, and were considerably below the voltages measured at the adjacent recorder poles. In general, however, the voltages at these arresters were considerably above those recorded at the other locations, which were in normal city territory.

Cable Poles. At cable poles the maximum voltages recorded were 78 kv between phase wire and ground, and 33 kv between phase wire and lead sheath. There were no indications of direct strokes. The indicated voltage of about 45 kv between lead sheath and ground may lead one to expect severe damage to the lead sheath caused by arcing from the sheath to the iron pipe risers at the cable poles. No such damage has been found on the Chicago system. The existence of voltage between the sheath and ground near the pothead may be due to the fact that the sheath is not grounded throughly until it is bonded to the rest of the cable system some distance from the pothead. When the sheath potential rises, the potential of the iron pipe lateral, which has resistance to earth, rises also with the probable result that there is insufficient potential built up between the sheath and this lateral to cause arcing.

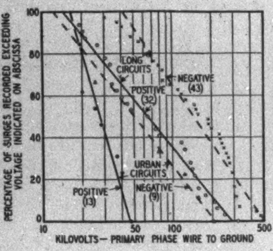

Fig. 4. Surge voltages due to lightning recorded on urban and "long" distribution circuits. Figures in parentheses are numbers of records obtained from primary phase to separate ground

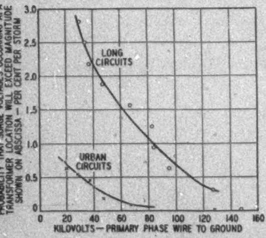

Fig. 5. Probability of voltages appearing at transformer locations during thunderstorms

Open Ends. The highest voltage recorded at the open ends of the primary mains was 205 kv to ground. In line with what would be expected on circuits of short length, the voltages at other recorders a few spans away (Fig. 7) were of the same general order. The statistical studies[1] had shown that transformers installed within 100 ft of the open end of primary lines had a rate of failure due to lightning about 20 per cent below the rate for other transformers.

Current Measurements. Voltages of 2.6 to 8.9 kv were recorded across the special thyrite disks in 31 of the 32 records, indicating discharge currents of about 300 amperes or less. In the remaining case the voltage was 15 kv corresponding to a discharge current of about 1,500 amperes. With such a current the lightning voltage would have to be several hundred kilovolts, which would have caused severe damage to the line. Since no damage was found, possibly this case is one where an error approaching 20 per cent applies.

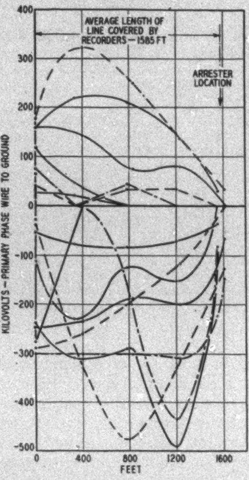

Fig. 6. Lightning voltages recorded on 2 "long" circuits. Each curve represents voltages obtained during 1 storm. Voltages shown as zero may have been as high as 20 or 25 kv

Transformers With Normal Arrester Protection. At one location, voltages were indicated on all 8 recorders at a transformer (Fig. 7). A voltage of 128 kv was recorded between the primary main and separate ground at the transformer, which is approximately the sum of the voltages recorded between primary phase and transformer case and between transformer case and separate ground. A voltage of 172 kv was recorded between the primary phase main and lighting secondary neutral main. This was the highest voltage recorded at transformer locations. (In some cases the voltage from primary phase wire to ground was more than from phase wire to secondary neutral.) The transformer fuse was not blown, largely eliminating the probability of a flashover at the bushings or an internal puncture that was later sealed up with oil.[5] The transformer on the pole was examined inside and outside and no arcing scars were found. Neither were there indications of flashover on the pole or recorders. Voltages recorded at transformers with normal arrester protection generally have been less than 100 kv.

Voltages of 30 and 37 kv have been indicated by recorders connected between the secondary phase main and the secondary neutral main at transformers. These are higher than would be expected, since the results of laboratory tests[6] have shown that only a few kilovolts can be built up across the secondary coils. In line with previous Chicago experience no trouble occurred at customers' premises as a result of these voltages at the transformers.

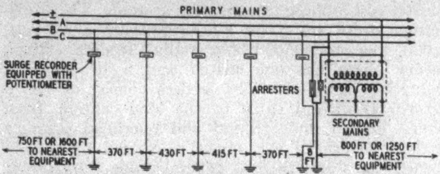
PRIMARY MAINS
±
A
B
C
SURGE RECORDER EQUIPPED WITH POTENTIOMETER
ARRESTERS
SECONDARY MAINS
750 FT OR 1600 FT TO NEAREST EQUIPMENT
370 FT
430 FT
415 FT
370 FT
8 FT
800 FT OR 1250 FT TO NEAREST EQUIPMENT

Fig. 7. Lightning voltages recorded at 1 location during 1 thunderstorm. In general, the voltages shown were among the highest obtained at such locations

Since recorders connected between the transformer case and separate ground were equipped with a potentiometer, the lowest voltage which could be recorded was about 18 kv. Only two records (18 and 25 kv) were obtained in these recorders, which gives some confirmation of staged tests[3] that the potential of the transformer case does not rise appreciably with the normal installation of arresters.

In all instances the potentials between the primary phase and transformer case were greater by about 2 to 1 than those recorded at the same locations between the primary neutral and case. These results are attributed largely to the difference in the arrester protection for the phase and neutral wires. In 7 of the 9 cases the difference did not exceed the difference in the breakdown values of the arresters.

Voltages as high as 82 and 100 kv were recorded between the primary phase and case, and at the same locations voltages of 62 and 172 kv were recorded between the primary phase and secondary neutral main. The maximum voltages recorded between primary phase and separate ground at *all* transformer locations were 158, 148, 128, 127, 95, 84, 83 kv, and 2 of 78 kv. No definite information on the time characteristics of these voltages is obtainable from the data. Because of the close spacing of arresters and transformers which is characteristic of most urban circuits and particularly of the major part of the Chicago system, it seems likely that the duration of these high voltages does not exceed a few microseconds.

Transformers With Interconnections. The outstanding data obtained at locations with interconnection (Fig. 3) were 13 kv across the transformer and 158 kv between the primary phase wire and separate ground. The interconnection definitely limited the voltage from the ends of the primary coils to the secondary neutral to the arrester voltage. The separate ground for the recorder connected between primary phase and ground had a resistance of 6 ohms. There was no evidence of a direct stroke on the pole.

Two other interesting records were obtained, 1 in which 15 kv was measured across the transformer and 78 kv was recorded between primary phase and ground, and 1 in which 13 kv was recorded across the transformer and 78 kv was recorded between primary phase and ground. In the first case the transformer fuse was blown. The transformer was examined on the pole and only 1 flashover was indicated by scars on the secondary neutral lead and case inside the transformer. The lead insulation may have been damaged by a previous surge. There was no scar to indicate from which lead the impulse had flashed to the case. The transformer was 22 years old.

Table III—Comparison of Lightning Voltages at Interconnected and at Normal Locations

Data Based on 5 Cases for Each Type of Arrester Installation

Type of Arrester Protection	Voltages—Kv Normal A	Interconnection B	Ratio B/A
Primary phase to separate ground	60	72	1.2
Primary phase to secondary neutral	57	15	0.26

Where voltages were recorded simultaneously between primary phase and ground and between primary phase and secondary neutral at interconnected and at normal locations (Table III), the benefit of the interconnection definitely is indicated. The voltage stress on the transformer insulation, that is, between primary winding and secondary neutral, was about 75 per cent less than for installations with normal arrester protection. The 2 years' operating experience of the Commonwealth Edison Company with the interconnection has indicated that troubles at transformers due to lightning, that is, transformers burned out and fuses blown, are reduced by about 65 per cent and the interconnection causes no adverse incidents in the customers' premises.

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2. INSTRUMENTS FOR LIGHTNING MEASUREMENTS, C. M. Foust. *General Electric Review*, v. 34, April 1931, p. 235.

3. LIGHTNING PROTECTION FOR DISTRIBUTION TRANSFORMERS, K. B. McEachron and L. Saxon. A.I.E.E. TRANS., v. 51, March 1932, p. 239.

4. INTERCONNECTION OF PRIMARY LIGHTNING ARRESTER GROUND AND THE GROUNDED NEUTRAL OF THE SECONDARY MAIN, C. F. Harding and C. S. Sprague. A.I.E.E. TRANS., v. 51, March 1932, p. 234.

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Radial Versus Primary Network Distribution

In this paper is set forth the comparative investment in distribution plant necessary over a 10-year period to provide for load increase in a typical section of Chicago, either by means of the existing radial feeder system or a primary network system. The results show that, in terms of both total new investment and accumulated annual costs, the use of the radial feeder system is the more economical in this case.

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Co., Chicago, Ill.

THE purpose of this study is to analyze the total investment required to serve a given area and to obtain comparative costs of providing for load increase in this area by means of 2 systems of distribution, (1) a 4-kv radial system, the standard type of distribution now used in Chicago, and (2) a 4-kv network system using unit type automatic substations as offered by the manufacturers. As shown in this paper, it is indicated that the extension of the radial system is more economical than the primary network system under the particular conditions existing in this Chicago area. Although the primary network may provide slightly better service continuity, the additional investment involved does not seem warranted.

BASIS OF THE STUDY

The area selected for study consists of about 6 sq miles in which the load is predominantly residential. The total investment values are based upon the plant in this area in 1929. At that time the distribution was by radial feeders from 4-kv substations located outside the area. It was apparent that substantial reinforcement of the distribution system within the area would be necessary in 1930. Two methods were possible: a new radial feeder substation; or a primary network installation. The comparison in this study is based upon the cost of installing these 2 systems to provide for load growth in the territory over a 10-year period from 1930. Only the incremental costs of those items which differ for the 2 systems are considered; that is, costs which are common to both systems are not included in the figures submitted.

DESCRIPTION OF SYSTEMS OF DISTRIBUTION

The radial system of supply consists of a new remote-controlled 4-kv substation supplied from the 12,000-volt 3-phase transmission system. The transformer units are 5,000 kva, supplying 4,000-volt, 1,000 kva and 2,500 kva radial feeders. Each feeder phase has one switch and a 10 per cent induction regulator. The feeders consist of No. 0 or 375,000-cir-mil cable to the load centers, from which extend underground and overhead primary mains. Overhead equipment is carried on jointly owned poles and there is generally one transformer per block, with the secondary mains not extending beyond the block in which the transformer is placed.

For the primary network, it was assumed that 4-circuit units would be used, supplied from the 12,000-volt transmission system. These units are of 1,500-kw transformer capacity, capable of carrying 2,000 kw with auxiliary air blast. They are to be installed on property purchased by the company. Bus regulation is to be provided. Tie mains between units are assumed to be overhead where possible, elsewhere 4-conductor No. 0 underground cable.

DESCRIPTION OF AREA

The area selected is of relatively recent development, consisting of 6.25 sq miles in the northwest part of the City of Chicago. It is mostly residential, with bungalows and houses, and some apartment buildings. There are the usual number of commercial customers, with a small amount of manufacturing in the southern portion of the area, but no customers large enough to require primary supply. Details are shown in Table I.

ASSUMPTIONS

In order to arrive at the probable load for the 10-year period considered, the load for the period

Table I—General Data, 1929

Area	Gross, 6.65 sq miles; net, 6.25 sq miles
Population density	10,000 per sq mile
Type of residence	medium bungalows and some apartments
Total underground circuit miles, primary	
In area	14 miles
To area	13 miles
Total overhead circuit miles, primary	
In area	86.4 miles
Number of distribution circuits	7–8
Average distance to load center	2.43 miles
Total kva load	6,250 kva, circuit maximum noncoincident
Customers supplied at primary voltage	none
Number of customers	18,200
Proportion of polyphase customers	2%
Kwhr sold, year	18,000,000
Proportion of kwhr sold to polyphase customers	25%
Demand at transformer secondaries	8,500 kva
Proportion of polyphase demand	20%
Load density, circuit demands	1,000 kva per square mile

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 23–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Nov. 20, 1933. *Not published in pamphlet form.*

between 1929 and 1932 was taken as base, and projected to 1939. (See Fig. 1.) The limit of voltage regulation allowed at radial feeder ends was taken as approximately one per cent. The average normal secondary pressure during load periods at the distribution transformer was taken to be 116 volts. The primary drop was assumed to be limited to 2 per cent. The area selected for study is shown in Fig. 2.

METHOD OF MAKING CALCULATIONS

Capital Investment. The original investment in plant in the area was obtained by a check of the property records as of the year 1929, and the application of unit costs. Investments in 4-kv substations and in the 12-kv transmission system, including switching at the generating stations, are allocated to the area in question by load proportions, since these items are not devoted to supplying this area exclusively. The results of this analysis are shown in Table II.

Incremental Investment. For both the radial and the network schemes of supply, an estimate was made of the investment necessary for added equipment to take care of the annual increase in load. The estimate covers distribution and transmission conduit and cable, substations, and such overhead ties as are necessary in connection with the network system. In figuring increment investment, it was not thought necessary to consider other items, such as distribution transformers, services, and branch mains, which are common to both systems. In the case of conduit, the cost of all of the conduit is charged as installed, rather than on a conduit-foot basis. Incremental investment for the 2 systems is shown in Tables III and VI.

Table II—Summary of Plant Investment, 1929

Item	Investment Dollars	 Per Cent
Transmission	$ 69,500	4.70
Substation	112,000	7.55
Underground primary conductors	132,700	8.95
Overhead primary conductors	88,900	6.00
Distribution transformers	85,440	5.75
Secondary conductors (overhead)	72,250	4.87
Services (overhead)	112,500	7.58
Conduits and manholes	552,400	37.20
Poles and fixtures	256,830	17.30
Total	$1,482,520	100.00

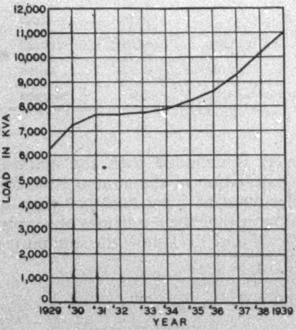

Fig. 1. Assumed noncoincident 4-kv circuit load in area. Loads for 1933 to 1939 were projected from the known 1929 to 1932 loads

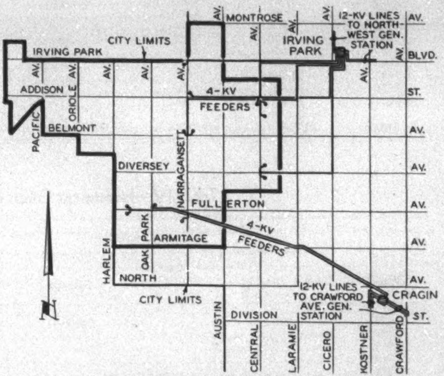
MONTROSE
AV.
12-KV LINES TO NORTH-WEST GEN. STATION
IRVING PARK
BLVD.
CITY LIMITS
IRVING PARK
ADDISON
ST.
4-KV FEEDERS
BELMONT
AV.
PACIFIC
ORIOLE
DIVERSEY
NARRAGANSETT
FULLERTON
4-KV FEEDERS
OAK PARK
ARMITAGE
HARLEM
NORTH
CITY LIMITS
12-KV LINES TO CRAWFORD AVE. GEN. STATION
CRAGIN
DIVISION
ST.
AUSTIN
CENTRAL
LARAMIE
CICERO
KOSTNER
CRAWFORD

Fig. 2. Area selected for study as it was supplied from 4-kv radial system in 1929

Adjacent streets shown are approximately 1/2 mile apart

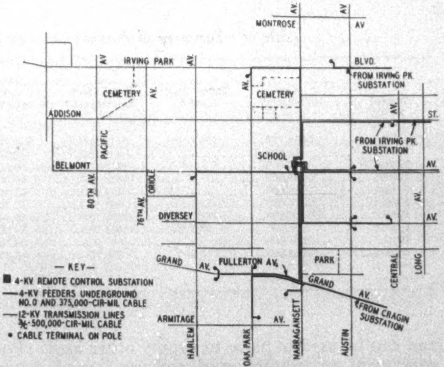
MONTROSE
AV
IRVING PARK
AV.
BLVD.
FROM IRVING PK. SUBSTATION
CEMETERY
CEMETERY
ADDISON
ST.
PACIFIC
FROM IRVING PK. SUBSTATION
SCHOOL
BELMONT
80TH AV.
76TH AV.
ORIOLE
DIVERSEY
GRAND
FULLERTON AV.
PARK
GRAND
FROM CRAGIN SUBSTATION
CENTRAL
LONG
ARMITAGE
HARLEM
OAK PARK
NARRAGANSETT
AUSTIN
— KEY —
■ 4-KV REMOTE CONTROL SUBSTATION
— 4-KV FEEDERS UNDERGROUND NO. 0 AND 375,000-CIR-MIL CABLE
— 12-KV TRANSMISSION LINES 3/C-500,000-CIR-MIL CABLE
• CABLE TERMINAL ON POLE

Fig. 3. First year (1930) of development of 4-kv radial plan of supply to area showing new substation and 4-kv feeders

Credits. Credits are based upon the actual original cost of equipment released. Credit is not taken for conduit vacated, substation space vacated, or substation transformers unloaded.

Retirement Reserve Charges. No charge has been included for equipment that is taken out of service

Table III—New Investment, 4-Kv Radial System

	Distribution		Substation			Transmission			
Year	Cable	Conduit	Land	Building	Equipment	Cable	Conduit	H. V. Switching	Total
1930	$ 46,620	$155,000	$9,000	$36,000	$112,100	$ 72,000	$65,000		$495,720
1931	4,280	5,000			7,700				16,980
1932	2,000	5,000							7,000
1933	2,000	5,000							7,000
1934	2,000	5,000			21,000				28,000
1935	2,000	5 000							7,000
1936	12,800	65,000			10,500				88,300
1937	13,500	5,000							18,500
1938	12,800	12,000			14,200	55,000	33,000	$6,000	133,000
1939	10,350	30,000							40,350
Total	$108,350	$292,000	$9,000	$36,000	$165,500	$127,000	$98,000	$6,000	$841,850

Table IV—Investment Credit and Retirement, 4-Kv Radial System

	Substation				Distribution			
Year	Est. Orig. Cost	Cost of Removal	Salvage	Retirement Reserve	Est. Orig. Cost	Cost of Removal	Salvage	Retirement Reserve
1930	$29,200		$29,200		$50,630	$2,710	$34,550	$18,790
1931								
1932								
1933								
1934								
1935								
1936								
1937	7,300		7,300		16,420	230	15,050	1,600
1938								
1939					7,600	840	3,100	5,340
	$36,500		$36,500		$74,650	$3,780	$52,700	$25,730

Table V—Summary of Annual Costs on Net Additional Investment, 4-Kv Radial System

Year	New Investment	Investment Credit	Net Addn'l Investment	Fixed Charges 11.2%	Mainte-nance	Energy Loss	Retirement Reserve	Total Annual Cost	Present Value at 7%
1930	$495,720	$79,830	$415,890	$46,300	$3,000	$3,860	$18,790	$71,950	$71,900
1931	16,980		432,870	48,400	3,100	3,990		55,490	51,900
1932	7,000		439,870	49,200	3,200	4,050		56,450	49,200
1933	7,000		446,870	50,000	3,300	4,155		57,455	46,900
1934	28,000		474,870	53,200	3,400	4,715		61,315	46,200
1935	7,000		481,870	53,900	3,500	4,930		62,330	43,900
1936	88,300		570,170	63,800	4,100	5,090		72,990	48,700
1937	18,500	23,720	564,950	63,300	4,100	5,050	1,600	74,050	46,200
1938	133,000		697,950	78,100	5,000	5,540		88,640	51,500
1939	40,350	7,600	730,700	81,800	5,200	6,270	5,340	98,610	53,500
					Present value of 10 years' annual costs				$509,900

and can be used in place to supply other load. For equipment actually removed, a charge is made based upon estimated original cost, plus the cost of removal, less a credit allowance. Credit and retirement items are shown in Tables IV and VII.

Annual Costs. In figuring the annual costs, the fixed charges were based upon a weighted average percentage on all added investment. The rate was taken at 11.2 per cent, and includes interest, taxes, depreciation, and insurance. Yearly energy losses were estimated to include losses on feeders, regulators, and substation transformers supplying the area, at a rate of $^1/_2$ cent per kilowatthour. Maintenance was estimated on a unit cost basis for the net added investment. In connection with the cut-overs from the radial system to the network, the cost of the cut-overs is included with the maintenance cost. The summation of the annual costs for the 2 systems, discounted at 7 per cent per year, is the basis for a comparison of the 2 schemes of supply for this area. Tables V and VIII show the summaries of annual costs.

PROVISION OF CAPACITY

Radial System. When the new substation was built, in the first year of the program, 6 1,000 kva feeders and one 2,500 kva feeder were installed. (See Fig. 3.) Due to the extensive rearrangement made necessary by the construction of the new substation, it was regarded as desirable to provide enough feeder capacity to care for the load growth

Table VI—New Investment, 4-Kv Network System

	Distribution			Substation			Transmission			
Year	Cable	Conduit	Ovhd. Ties	Land	Installation	Equipment	Cable	Conduit	H. V. Switching	Total
1930	$ 8,780	$118,000		$ 9,000	$ 9,400	$ 67,800	$ 80,000	$65,000		$ 357,980
1931	8,100	20,000	4,530	9,000	9,400	56,800	15,000			122,830
1932		5,000								5,000
1933		5,000								5,000
1934	2,730	15,000	7,410	9,000	9,400	56,800	11,000			111,340
1935	2,900	13,000	3,120	4,500	4,700	28,400	7,000			63,620
1936	9,520	68,000	4,437	4,500	4,700	28,400	4,000			123,560
1937	4,650	31,000	2,900	4,500	4,700	28,400	1,000			77,150
1938	4,050	33,000		4,500	4,700	28,400	71,000	33,000	$6,000	184,650
1939	6,000									6,000
Total	$46,730	$308,000	$22,400	$45,000	$47,000	$295,000	$189,000	$98,000	$6,000	$1,057,130

Table VII—Investment Credit and Retirement, 4-Kv Network System

	Substation				Distribution			
Year	Est. Orig. Cost	Cost of Removal	Salvage	Retirement Reserve	Est. Orig. Cost	Cost of Removal	Salvage	Retirement Reserve
1930					$10,230	$ 420	$ 8,680	$ 1,970
1931	$14,600		$14,600		24,490	1,030	18,380	7,140
1932								
1933								
1934	14,600		14,600		33,340	780	28,490	5,630
1935								
1936					520		520	
1937	7,300		7,300		6,720	490	3,750	3,460
1938								
1939								
Total	$36,500		$36,500		$75,300	$2,720	$59,820	$18,200

Table VIII—Summary of Annual Costs on Net Additional Investment, 4-Kv Network System

Year	New Investment	Investment Credit	Net Addn'l Investment	Fixed Charges 11.2%	Maintenance and Cutover	Energy Loss	Retirement Reserve	Total Annual Cost	Present Value at 7%
1930	$357,980	$10,230	$347,750	$ 38,900	$3,500	$3,240	$1,970	$ 47,610	$ 47,600
1931	122,830	39,090	431,490	48,300	4,100	3,095	7,140	62,635	58,500
1932	5,000		436,490	48,900	3,100	3,100		55,100	48,100
1933	5,000		441,490	49,400	3,200	3,100		55,700	45,400
1934	111,340	47,940	504,890	56,500	4,600	2,760	5,630	69,490	52,300
1935	63,620		568,510	63,600	4,600	3,035		71,235	50,300
1936	123,560	520	691,550	77,400	5,500	3,320		86,220	57,600
1937	77,150	14,020	754,680	84,500	5,900	3,320	3,460	97,180	60,600
1938	184,650		939,330	105,100	7,200	3,290		115,590	67,200
1939	6,000		945,330	105,800	7,300	3,065		116,165	63,000
					Present value of 10 years' annual costs				$550,600

Table IX—Comparative Load-Capacity Table

		Radial Plan			Network Plan		
Year	Load Kva	Radial Feeder Capacity From Outside of Area Kva	Radial Feeder Capacity From New Substation Kva	Total 4-Kv Feeder Capacity Kva	Radial Feeder Capacity From Outside of Area Kva	Network-Unit Capacity @ 1500 Kva Per Unit Kva	Total Capacity Network-Unit Plus Radial Feeders Kva
1930	7,225	3,000	8,500	11,500	7,000	3,000	10,000
1931	7,680	2,500	9,500	12,000	5,000	6,000	11,000
1932	7,645	2,500	9,500	12,000	5,000	6,000	11,000
1933	7,725	2,500	9,500	12,000	5,000	6,000	11,000
1934	7,900	2,500	9,500	12,000	3,000	9,000	12,000
1935	8,200	2,500	12,000	14,500	3,000	10,500	13,500
1936	8,600	2,500	12,000	14,500	2,500	12,000	14,500
1937	9,300	1,500	12,000	13,500	1,500	13,500	15,000
1938	10,200	1,500	14,500	16,000	1,500	15,000	16,500
1939	11,000	1,500	14,500	16,000	1,500	15,000	16,500

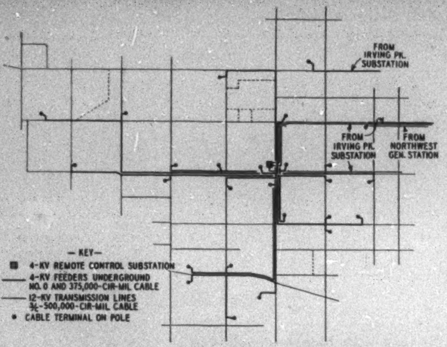
FROM IRVING PK. SUBSTATION
FROM IRVING PK. SUBSTATION
FROM NORTHWEST GEN. STATION
— KEY —
4-KV REMOTE CONTROL SUBSTATION
4-KV FEEDERS UNDERGROUND NO. 0 AND 375,000-CIR-MIL CABLE
12-KV TRANSMISSION LINES 3/c-500,000-CIR-MIL CABLE
CABLE TERMINAL ON POLE

Fig. 4. The 4-kv radial plan of supply to area as developed at end of tenth year (1939)

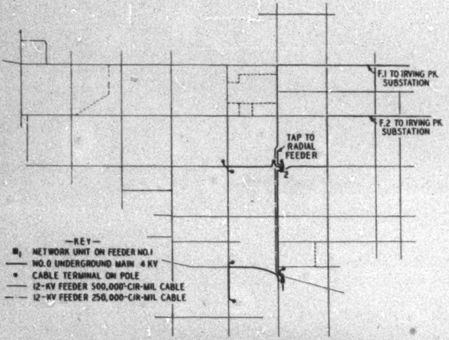
F.1 TO IRVING PK. SUBSTATION
F.2 TO IRVING PK. SUBSTATION
TAP TO RADIAL FEEDER
2
1
—KEY—
1 NETWORK UNIT ON FEEDER NO.1
NO. 0 UNDERGROUND MAIN 4 KV
CABLE TERMINAL ON POLE
12-KV FEEDER 500,000-CIR-MIL CABLE
12-KV FEEDER 250,000-CIR-MIL CABLE

Fig. 5. First year (1930) of development of primary network plan of supply to area showing new network units and feeders superimposed on radial system shown in Fig. 2

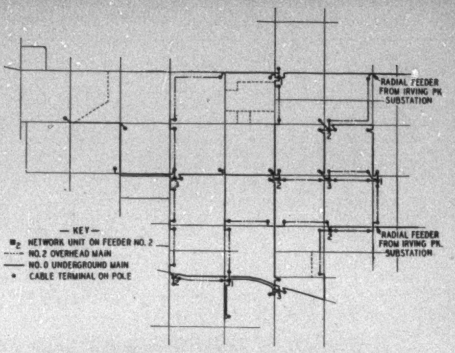
RADIAL FEEDER FROM IRVING PK. SUBSTATION
RADIAL FEEDER FROM IRVING PK. SUBSTATION
— KEY —
2 NETWORK UNIT ON FEEDER NO. 2
NO. 2 OVERHEAD MAIN
NO. 0 UNDERGROUND MAIN
CABLE TERMINAL ON POLE

Fig. 6. The 4-kv mains for primary network plan of supply to area as developed at end of tenth year (1939)

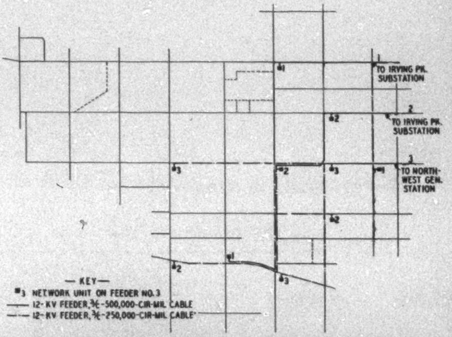
TO IRVING PK. SUBSTATION
TO IRVING PK. SUBSTATION
TO NORTH-WEST GEN. STATION
1
2
3
— KEY —
3 NETWORK UNIT ON FEEDER NO. 3
12-KV FEEDER, 3/c-500,000-CIR-MIL CABLE
12-KV FEEDER, 3/c-250,000-CIR-MIL CABLE

Fig. 7. The 12-kv feedess for primary network plan of supply to area as developed at end of tenth year (1939)

in the area for a somewhat longer period than would be customary otherwise. However, unexpected local development required the installation of another 1,000 kva feeder in the second year. No further reinforcement was found to be necessary until the sixth and ninth years, in each of which a 2,500 kva feeder is installed. Of the 7 feeders originally supplying the area, 4 were removed in the first year and one in the seventh year. In addition, about one-half the capacity of one feeder was released for use outside the area in the second year. The new substations and 4-kv feeders in service at the end of the tenth year are shown in Fig. 4. The net amount of feeder capacity in service in any year is shown in Table IX.

The original transformer installation in the new substation consisted of 2 5,000-kva, 3-phase units, the supply to which was from 2 12-kv transmission lines. In the fifth year of the program a third 5,000 kva unit was added, and in the eighth year an additional 12-kv transmission line to the station was necessary.

Network System. The plan followed with this system was to provide capacity in the form of network units as required, utilizing the original radial feeder capacity in the area to as great an extent and as long as possible. Consequently, only 2 units and 2 12-kv transmission lines were installed the first year of the program. (See Fig. 5.) Following this, 2 units were installed in the second year, 2 in the fifth year, and 1 each in the sixth, seventh, eighth and ninth years. A third transmission line was required in the eighth year. In carrying out this development 2 radial feeders were removed in the second year, 2 in the fifth year, and 1 in the eighth year. In addition, about one-half the capacity of 1 feeder was released for use outside the area in the seventh year. The units and principal mains in service in the tenth year are shown in Fig. 6, and the 12-kv feeders are shown in Fig. 7. The combined network and radial feeder capacity in service in any year is shown in Table IX.

Discussion of Results

Although the total normal capacity in service on the 2 systems is different in various years, generally speaking the firm capacity of the 2 is the same. This apparent discrepancy is due partly to the inherently different availability of reserve on the 2 systems.

Comparison of the various investment items in the 2 plans shows that the investment in distribution cable for the network is much less than for the radial system. The difference in the 2 is about balanced, however, by the additional cost for transmission cable on the network system, which represents the primary laterals for the purpose of supplying the scattered network units. These primary laterals perhaps could be regarded as distribution cable with some justification, but here are classed as transmission. The fact that the distribution conduit in the 2 schemes is about the same while the distribution cable is much less in the case of the network is due to the fact that on the network plan no attempt was made to distinguish between conduit occupied within the area by network mains and that occupied by primary laterals, all such conduit being classified under distribution.

Conclusions

The analysis shows that, for the conditions upon which this study was based, the net new investment and accumulated fixed charges for the extension of the radial system are less than they would be for the provision of the necessary reinforcement by means of a primary network.

Although there is some reason to believe that the primary network provides slightly better service continuity when fully developed than does the radial system, the improvement does not seem to warrant the additional investment involved. The other factors, such as the uncertain period of development and experimentation in service before its full advantages may be realized, and the multiplication of public relations problems due to occupying many substation sites, detract from the desirability of the network system. It is, of course, recognized that for certain load densities and rates of growth, or in comparison with some other existing systems, the primary network might have an economic advantage.

Electrical Equipment for Induction Furnaces

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Although frequencies now are standardized in the melting field and soon will be in the heating field, most types of furnaces require special equipment. The electrical equipment discussed in this paper includes the frequency converters, the switching, and the capacitors. Typical installations are shown and the advantages and possibilities of water-cooled equipment are mentioned.

THE APPLICATION of the inductive method for heating or melting requires electrical equipment of somewhat special character. Normal frequency supply cannot be used economically except in a few instances. Furthermore, the induction furnace is essentially a single phase load. For these reasons a motor-generator set is necessary in most cases, although some "core" type furnaces and furnace of the spark gap oscillator type can be connected to the normal frequency supply lines. In spite of the drawback of special and consequently more expensive electrical equipment, the use of induction furnaces has spread rapidly. This type of furnace has many advantages, particularly in the field of special alloy steels. Its basic principles, its design and practical applications have been discussed fully in previous papers and current literature. (See bibliography at end of paper.)

Classification of Furnaces

There are 2 commercial types of induction furnaces: (1) the "core" type and (2) the "coreless" type. The first type uses a core of transformer iron for the magnetic circuit, whereas the second type (Fig. 1) has no closed magnetic circuit of iron. The core type either uses normal frequency or subnormal low frequency and a strong magnetic field while the coreless type uses a weak magnetic field but high frequency. The coreless type may be supplied by rotating generating equipment or by static high frequency spark gap or vacuum tube oscillator equipment. The core type also needs rotating

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Full text of a paper recommended for publication by the A.I.E.E. committee on electrochemistry and electrometallurgy, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 23–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Nov. 16, 1933. *Not published in pamphlet form.*

generating equipment for low frequency although normal frequency furnaces have been designed. The chief objection to the use of normal frequency is the violent stirring of the charge due to the action of electromagnetic forces. Because of the expense involved in large capacity low frequency generators, and the necessity for preventing freezing of the charge in the furnace the core type of furnace now is confined chiefly to the non-ferrous field and most of the ferrous melting installations are of the coreless type.

The coreless induction furnace is subdivided further by the range of high frequency employed and the apparatus used for generating it. When capacity exceeds 50 kw for melting applications 960 cycles is the standard frequency, although 480 cycles was used in earlier installations. For the smaller melting and heating capacities the spark gap oscillator or the vacuum tube oscillator is best fitted to furnish frequencies of the order of 20 kilocycles and higher which then can be used economically. Theoretically frequencies of this order could be used to advantage in the large capacity units also but the expense of the special rotating equipment needed would not be justified.

In heating applications the range of desirable frequency will be greater because of variation in the dimensions of the charge, and the conditions under which the heat energy must be applied. The power absorbed by the charge is proportional to the frequency used and the square of the ampere turns of the inductor coil, while the minimum frequency for effective transfer of energy to the charge is a function of the diameter of the charge and its resistivity.

Fig. 1. Two 600-lb coreless furnaces powered by a 300-kw 960-cycle generator

For these reasons the frequency used in many cases will be a compromise between the economic and the theoretical best frequency. Obviously the use of many different frequencies would not be practical because of the additional expense required for each generator. For such heating applications where normal frequencies cannot be used it is likely that 360 or 480 cycles in the lower ranges and 4,800 or 5,000 cycles in the higher ranges will become standard.

Because no new principle is involved but only a difference in temperature range and operating methods, the equipment described includes heating as well as melting applications.

The electrical equipment includes:

1. Motor-generator frequency converters.
2. Control panels for both motor and generator.
3. Capacitors for correction of furnace power factor.
4. Control and switching of capacitor units.
5. Miscellaneous equipment, such as inductor tap switches.

Frequency Converters

The single phase generators of these converters usually are driven by standard induction motors or synchronous motors. If the drive is synchronous 2 exciters are required, one for the generator and the other for the motor.

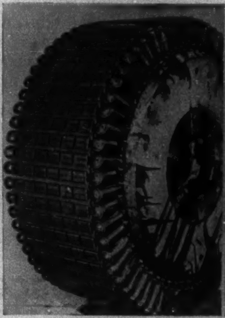


Fig. 2. Rotor of 300-kw 960-cycle single-phase salient pole generator

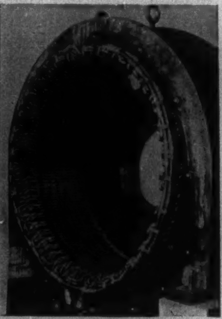


Fig. 3. Stator of 300-kw. 960-cycle single-phase salient pole generator

From the designers' standpoint the generator is a special one because the large number of poles even at the highest speed allowable results in special construction, and affects the electrical characteristics of the design. The rotor of a 300-kw generator illustrated in Fig. 2, in appearance resembles the rotor of a wound rotor motor. The poles, however, are well defined salient poles. Special construction is needed because of the very small pole pitch. The cap screws are passed through each end of the coil as it projects from the rotor; at each end of the rotor these screws are threaded into a plate which is fastened securely to the rotor spider.

Since the number of slots per pole is so low, the stator reactance is comparatively large, which results in increased field current. It is for this reason that designing these machines (Fig. 3) for any power factor other than unity becomes uneconomical. Another special feature inherent to this type of design is a comparatively large ratio of core length to pole pitch. This makes ventilation a more difficult problem. For this reason the ventilating system differs from that used for normal frequency generators. The ordinary arrangement is to have air coming from each end between the field poles and discharging through stator vents. On these machines, however, it is necessary to bring air through ducts in the rotor because the space between field poles is far too small for that purpose.

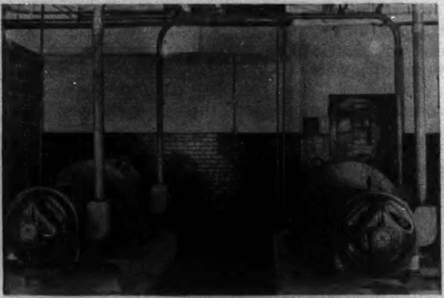


Fig. 4. Two 60-kw 3,600-rpm 4,800-cycle single-phase inductor type water-cooled generators with induction motor drive

Machines usually are built open, depending upon the normal ventilation of the room in which the machine is located. In some cases where the substation is small or the air not clean special precautions must be taken to supply the machines with clean air under slight pressure or supply forced ventilation. In such cases a machine totally enclosed with built-in circulating system and provision for cooling the circulating air by water may prove more economical and satisfactory than systems of substation ventilation, particularly if the air has to be cleaned as well as cooled.

When higher frequencies such as 4,800 or 5,000 cycles are required, the inductor type of generator design, which involves no windings on the rotor, can be used. Due to the absence of pole windings space limitation which hampers the salient pole design is removed, and the requisite number of poles can be obtained for the high frequency needed, without exceeding allowable peripheral speeds. Two generators of this type are shown in Fig. 4. The machines are enclosed, and water cooling provided to remove the heat losses from both stator and rotor.

The fundamental construction of the generator is shown schematically in Fig. 5. The rotor is a solid cylindrical disk pressed on a supporting spider. The surface of the rotor is slotted so as to cause a nearly sinusoidal variation in the field flux, with the required frequency. The field is wound in a slot between the 2 inner frames, and is covered by the outer frame. The stator core is cooled directly by imbedded water pipes, while the heat from the rotor is extracted by the circulating air which in turn is cooled by 2 circular water cooling coils at each end.

Also, the enclosing end bells serve materially to reduce the noise usually associated with the open type high frequency generator. The efficiency of these high frequency generators is lower than 60-cycle units of corresponding capacity. This is due to higher iron and load losses. Comparative efficiencies could be obtained only by a greater increase in the cost than is economically justifiable.

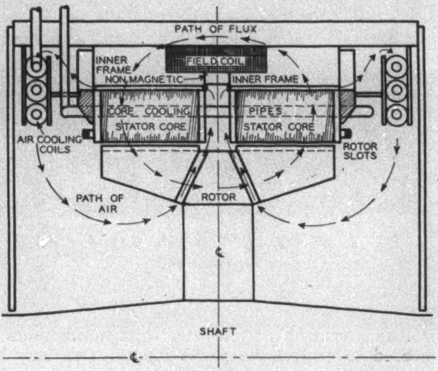

PATH OF FLUX
INNER FRAME
FIELD COIL
NON MAGNETIC
INNER FRAME
CORE COOLING PIPES
STATOR CORE
STATOR CORE
AIR COOLING COILS
ROTOR SLOTS
PATH OF AIR
ROTOR
℄
SHAFT
℄

Fig. 5. Cross section of water cooled inductor type generator

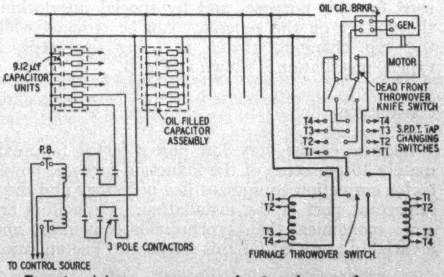

OIL CIR. BRKR.
GEN.
MOTOR
DEAD FRONT THROWOVER KNIFE SWITCH
9.12 µf CAPACITOR UNITS
OIL FILLED CAPACITOR ASSEMBLY
T4
T3
T2
T1
T4
T3
T2
T1
S.P.D.T. TAP CHANGING SWITCHES
P.B.
T1
T2
T3
T4
T1
T2
T3
T4
3 POLE CONTACTORS
TO CONTROL SOURCE
FURNACE THROWOVER SWITCH

Fig. 6. Main connections for 2 induction furnaces operating from a single generator and capacitor bank

The triple series contactor shown simply represents the use of 3 550-volt units assembled for 1,250-volt service

Control Panels

The control for these motor-generator sets is very simple. The metering equipment includes alternating current ammeter, wattmeter, voltmeter, and power factor meter designed and calibrated for the frequency used. A direct current field ammeter, automatic voltage regulator, field switch, generator oil circuit breaker, and overload relay complete the equipment generally used. When 4,800 cycles is used the field switch is replaced by a field contactor to permit "killing" the field of the generator when the overload relay operates, since an oil circuit breaker for this frequency would have to be specially designed.

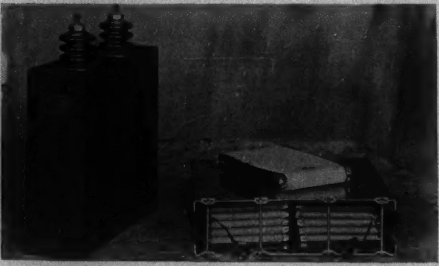


Fig. 7. A 900-volt 960-cycle 9.12-μf oil-filled capacitor unit

Adjustment of the generator voltage sometimes is needed to control the power input. This may be done readily by a voltage adjusting rheostat on the regulator. However, for any particular heat cycle, adjustment of power input can be made by changing the inductor taps. Hand operated switches are used for this purpose, and by special interlocking the voltage on the generator can be reduced while the tap changing switch is being operated. A typical installation is shown in Fig. 6.

CAPACITORS

Because of the very low power factor (approximately 10 per cent) of the induction furnace, power factor correction equipment is a necessary and most important part of the installation. Capacitors are more economical than synchronous condensers and invariably are used for this purpose. The equation

$$\text{Kva} = \frac{2\pi f\, CE^2}{10^9} \qquad (1)$$

indicates that the kilovoltampere rating of a capacitor increases directly with the frequency. That is to say, a 5-kva, 60-cycle unit will deliver 80 kva on 960 cycles at constant voltage. Over the range from 60 to 960 cycles the power factor and dielectric strength are substantially constant so that although the losses will increase in proportion to the increased rating, it is possible by special design and suitable cooling to remove them at a rate that will keep the temperature rise of the dielectric within a satisfactory limit of 25 deg C.

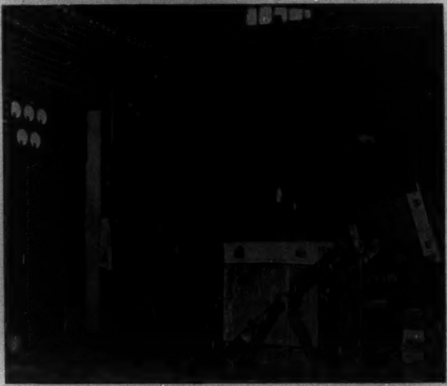
Above this range of frequency several important considerations limit the application of this equation to determine the rating.

1. The power factor increases, and therefore the losses no longer increase at a linear rate with the frequency.
2. The dielectric strength tends to decrease so that at 2,000 cycles it is about 70 per cent of its value at 60 cycles.
3. No matter how effective the heat transfer from the case of the unit may be, nor how careful a design is made the temperature gradient in the dielectric becomes too great and temperature rise exceeds a safe working value. It is desirable, therefore, for frequencies in excess of 1,000 cycles to derate the capacitor to allow for these conditions.

In actual practice, the standard oil-filled 9.12-μf, 900-volt unit is rated at 45 kva on 960 cycles. This unit is mounted with several others in an oil filled tank, with water cooling coils for removing the heat from the oil. The complete battery of capacitors consists of a number of these water-cooled tanks mounted as close as possible to the furnace. Some of the important features of construction used in making this unit are:

1. The use of aluminum foil 0.00033 in. thick.
2. The foil is extended $^1/_2$ in. beyond the ends of the paper instead of buried in the paper as in the ordinary type of construction, the $^1/_2$ in. extension of the foil serving as a cooling fan.
3. The unit is built in 2 sections as shown in Fig. 7 separated in the middle to form a vertical oil passage, the 2 sections then are connected in series. This construction serves to distribute the heat conducting material through the dielectric.
4. Special precautions are taken to carry the heavy currents by riveting and soldering the terminal leads to the foil extensions.

Fig. 8. Typical induction furnace installation: (left) the motor-generator set, motor control panels, and water-cooled capacitor assembly; (below) furnace and control



The rest of the construction follows standard practice for power type capacitors, the sections being wound and heat treated in special vacuum dehydrating furnaces before impregnating in oil. Future possibilities are improvements in the construction and cooling methods and materials of impregnation, so that it is quite possible that further economies in application of these units may be effected.

The power factor of the furnace varies considerably during a heat cycle and provision must be made for increasing the number of capacitor units as the heat progresses. Table I illustrates the variation in voltage applied to the furnace by change in the inductor tap switches. It shows also the variation in the number of capacitor units connected in parallel with the furnace inductor and the kilovoltamperes per unit at different parts of the heat cycle.

Table I—Heat Cycle of a 1-Ton 300-Kw 960-Cycle Furnace

Time	Gen. Volts	Gen. Amp	Gen. Kw	Gen. % P. F.	Cap. Volts	No. Cap.	Cap. Unit Kva	Furn. Taps
1:10	800	420	315	96*	1250	36	84	2-3
1:17	805	300	230	100	1260	43	86	2-3
1:22	780	340	260	100	1090	43	64	2-4
1:27	800	340	260	98.5†	1120	43	68	2-4
1:32	795	345	260	98	1115	43	67	2-4
1:37	800	365	280	100	1120	43	68	2-6
1:42	800	390	300	98.5†	1020	45	56	1-3
1:45	800	390	300	98+	930	49	47	1-4
1:48	810	405	320	97.5†	945	50	48	1-4
1:53	795	410	310	100	930	55	47	1-4
1:58	800	420	320	98†	930	56	47	1-4
2:07	800	430	330	98†	930	56	47	1-4

* Leading power factor.
† Lagging power factor.

The general arrangement of an induction furnace installation is shown in Fig. 8. The small brick building houses the motor-generator set, while the control panel is shown inserted in one side of the front wall. There are 2 furnaces 1 on each side of the substation building.

Fig. 9. Installation of water-cooled conductors

The miscellaneous equipment such as furnace tap switches and bus connections are of special interest only in installations where large currents are involved. In one large installation the currents between the condenser bank and the furnace were more than 12,000 amperes. A normal type of construction was out of the question because of the inductive reactance of multiple conductors required for such currents. An extremely neat and clever solution of the difficulty was worked out by the use of water-cooled conductors (Fig. 9). The conductors consisted of water-cooled tubes and high current density so that only a few conductors were required.

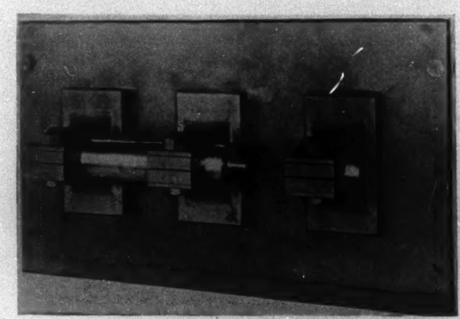


Fig. 10. Water-cooled switch unit

Figure 10 shows a water-cooled switch unit which could be used to great advantage in a layout such as that illustrated in Fig. 9 where the use of the ordinary type of knife switch made it necessary to spread the conductors. With a switch like the one illustrated a far more compact installation is possible and inductive drop can be greatly reduced. Judging from the past growth of this type of furnace, larger installations may be expected in the future, and designers will have to consider the problems of generating and transmitting large currents at high frequency. For transmitting, water-cooled conductors undoubtedly will answer the purpose; special methods of connection will have to be used in generation.

Parallel operation of generator units is perfectly feasible, so that there is no reason from the electrical equipment standpoint, why larger installations than those already existing cannot satisfactorily be supplied with energy at high frequency.

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Automatic Reclosing of Oil Circuit Breakers

Solutions for various problems encountered in connection with the automatic reclosing of oil circuit breakers are given in this paper. The results of studies made by several companies, and a brief description of devices for this type of service, also are given.

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THE APPLICATION of automatic reclosing to oil circuit breakers covers a period of about 12 years. Although there are a few scattered applications antedating this period, and such applications have been duly recognized, nevertheless the broader and more general use of this type of switchgear may be said to have its inception around 1921.

It is estimated that the rated load handled by this type of equipment (in this country) is in excess of 10,000,000 kva, this figure representing over 50 per cent of the installed capacity of automatic switchgear. The advantages gained were at once apparent and the extent of the installed capacity is indicative of the industry's reception of this development. A majority of the applications fall in the 2,300–4,600 volt class, with a maximum of 154 kv. Practically all applications have been on stub or radial feeders, and as this type of feeder is typical, this paper is confined to stub feeder application.

A greater part of the earlier installations was made on feeders on which lighting load predominated. A commonly accepted reclosing cycle was 15–30–75 sec, this cycle continuing in use up to the present time. The 15-sec interval was an arbitrary choice, and represented a marked improvement over previous manual reclosing, sufficing as a minimum value for several years. The remaining intervals also were arbitrarily chosen, with some consideration toward lessening the duty on the oil circuit breaker in case of successive operations.

Occasionally the question is raised concerning the possibility of automatically measuring the impedance of an a-c feeder, in order to determine whether or not the breaker should reclose. This method has been used for a number of years on d-c railway and industrial circuits. Such equipment for a-c circuits, has been built and tested but the results were not successful from an economic point of view due to a number of reasons. First, a large part of the load on the conventional a-c circuit consists of lamps, whose "cold" resistance may be only 10 per cent of the "hot" resistance. If a small load indicating or load measuring current is used, it is difficult to distinguish the difference between a short circuit and useful load. Another requirement is the detection of high resistance cable faults or defective insulators which may not break down until practically normal voltage is reached, subsequently developing into faults of low impedance. Although the measuring current and voltage may be increased, the few additional advantages do not warrant the increase in cost over the simple equipment which recloses the breaker, regardless of circuit conditions.

Operating experience over several years has indicated the practicability of reclosing the a-c feeder breaker without the use of load indicating equipment. Soon after a-c reclosing equipment began to be applied more generally, it was found that from 75 to 90 per cent of the breaker openings were caused by transient faults that disappeared after the first, second, or third opening.

Delayed Versus Immediate Initial Reclosure

During 1931 the Alabama Power Company, Georgia Power Company, Tennessee Electric Power Company, and the West Penn Power Company made a systematic study of the percentage of successful reclosures utilizing time delay. This study was made on overhead transmission feeders, from 2.3 to 110 kv, with reclosing cycles in the range of 15, 45 to 60, and 60 to 120 sec. During this period approximately 2,900 initiating operations were observed (initial breaker trip-out starting a reclosing cycle, which continues until successful reclosure or lockout) with the following percentage of successful reclosures and lockouts:

Reclosure	*Breaker Remained Closed*
First	86.9%
Second	3.4%
Third	0.9%
Lockout	8.8%

The time delay, before reclosure, for general application was governed largely by breaker derating

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Full text of a paper recommended for publication by the A.I.E.E. committee on protective devices, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Nov. 24, 1933. *Not published in pamphlet form.*

factors and only in a few isolated cases, such as allowing time for synchronous or other machinery to become disconnected, were load requirements given the consideration that would lead to better service.

During 1932 the first 3 of the companies mentioned conducted another general investigation, during which period there was recorded the results obtained from the operation of a large number of feeders, ranging from 2.3 to 66 kv, and equipped for immediate initial reclosure, that is, without any purposely added time delay. Over 1,600 initiating operations took place during this period with the following results:

Reclosure	*Breaker Remained Closed*
First	73.3%
Second	15.9%
Third	2.8%
Lockout	8.0%

The reclosing cycles used during this period were:

0– 15–120 sec
0– 60– 60 sec
0–120 sec (no third reclosure)

Although the percentage of successful first reclosures was less with immediate reclosure, actually it meant that 73.3 per cent of the faults did not develop interruptions to service from the consumer's point of view, and that 18.7 per cent were considered interruptions, in addition to 8 per cent lockouts, as contrasted with 91.2 per cent interruptions in addition to 8.8 per cent lockouts, where a time delay of 15 sec or more was used for the initial reclosure.

On the Georgia Power Company's system, practically all feeder and many tie line (44 kv and below) breakers have been equipped with the 0–15–120 sec reclosing cycle. The record of 1,010 initiating operations, during 1933, is given in the following:

Reclosure	*Breaker Remained Closed*
First	88.7%
Second	4.5%
Third	1.3%
Lockout	5.5%

The above data mark an improvement over the 1932 performance record and are attributed largely to more alert inspection and maintenance of lines and breakers, better tree trimming and improvement in automatic reclosing devices. The trend in improved operating service is evident readily upon consulting these tables.

The values in the foregoing tables show that the percentage of successful third reclosures forms, in general, an appreciable quantity in comparison with the percentage of lockouts. In other words, if the third reclosure had been omitted it would have increased the lockouts by approximately 25 per cent. Furthermore, the third reclosure can be obtained in the conventional design of a-c reclosing relay with practically no additional expense or complication.

Factors to Be Considered in Connection With Immediate Initial Reclosure

The improvement in service resulting from the use of immediate initial reclosure cannot be obtained without first taking into consideration some conditions which were of secondary importance when time delay initial reclosure was employed. These factors are given in the following paragraphs:

Cause of Outages. A greater portion of the faults on overhead a-c distribution systems are of a transitory nature. The usual types of faults are insulator flashovers, swinging faults, and short circuits. When flashovers occur, the fault may be cleared by removing the voltage long enough to extinguish the arc and to be certain that the arc path has recovered its dielectric properties. In the case of a swinging fault there also is a reasonable chance that the fault can be removed by opening and quickly reclosing the circuit breaker. (Some swinging faults may persist longer than the initial reclosing period, and therefore will require the second reclosure.) Short circuits of a permanent nature are the most probable cause of lockouts.

Primary distribution lines of 2,300 to 4,600 volts constitute a very substantial part of the total distribution system. It has been found that wind, sleet, trees, lightning, public interference, and foreign lines account for a high percentage of outages to the consumer, due to the comparatively high exposure of the lines to these conditions. Consequently it can be seen that proper sectionalizing plus automatic reclosing can improve the service now obtainable under multicircuit grouping.

Induction and Synchronous Motor Load. During the period that the fault exists on the feeder and the circuit breaker is in the open position, any motor connected to the feeder will, in all probability, be operating at reduced or zero voltage. This will retard the speed and may be ruinous to certain products. Even though the product is not affected, there may be cases where the motor cannot return to normal speed when the feeder voltage is restored. In many cases the products are not affected and intervals of 2 to 4 sec have been encountered without ill effect.

Generally speaking, induction motors will return to normal speed from any reduced value, inasmuch as their load usually is connected directly from standstill to normal operating speed. However, the longer the deënergized period the greater the decrease in speed, resulting in higher inrush current, which, at its poor power factor, gives a greater amount of line drop, and subsequent delay in returning to normal operating voltage.

Synchronous motors will not necessarily pull their load back to normal speed after a voltage interruption. Their ability to return to normal speed under this condition depends largely on pull-in torque and load characteristics. Those motors (50 to 60 per cent) that can resynchronize under load from any decrease in system voltage or from subnormal speed, will, in all probability, require automatic field removal and resynchronizing equipment. Such equipment is readily available. Those motors (40 to 50 per cent) that cannot resynchronize due to torque or load characteristics will require, in addition, suitable unloading features. Although in some cases synchronous motors have remained connected, after an interruption, without the use of the above equipment, such cases usually can be accounted for by certain load conditions or the presence of sufficient reactance in the system to absorb the out of phase current. Synchronous motors (due to a small amount of stored energy) pull out of step rapidly, under conditions of reduced voltage, when carrying full load. Under this condition they can stand complete loss of voltage for only 2.5 to 5 cycles and still remain in synchronism. The restoration of normal operating voltage within this extremely short period is not available with present equipment. Furthermore, a period of 2.5 to 5 cycles, without voltage, may not be long enough to allow the dielectric in the path of the fault to recover its insulating properties to a degree that will permit successful reëstablishment of normal operating voltage.

Synchronous motors (and condensers) tend to maintain arcs caused by the fault. Obviously the duration of these arcs will affect the choice of a suitable reclosing interval. Field tests and operating experience will be required before the effects of this characteristic on the general problem are fully known.

Lighting Load. Lighting load imposes no serious problem in connection with immediate reclosing. A reduction in the period of outage from a number of seconds to a second or less, will be of mutual advantage to the consumer and operating company.

Undervoltage Devices on Motor Controllers. Practically all motor controllers are equipped with some form of undervoltage protection; and, if service conditions are to be improved by quick reëstablishment of voltage, these devices must not disconnect the motor controller during the reclosing period. Instantaneous undervoltage devices, as a class, will not fulfill this requirement, since they will drop out within a few cycles after voltage has decreased below their drop-out value. Time delay undervoltage devices are required in order to take full advantage of the immediate initial reclosing cycle. The available timing interval of the undervoltage device for use with immediate reclosure should be long enough to overlap (1) the duration of the fault (which may decrease the voltage to something below the drop-out value of the device), (2) the time the breaker is open, and (3) the time it may require system voltage to return to at least the pick-up value of the device. In many cases normal voltage returns immediately with the closing of the circuit breaker, but there are cases where long lines coupled with heavy inrush current at a lagging power factor delay the return of the voltage to its normal value. A suitable drop-out value may reduce somewhat the required time delay but care must be taken to see that this value is not so low that other operating characteristics of the device are sacrificed.

A general consideration of this problem, together with a limited amount of operating data, has indicated that a device providing a time delay of 1 to 3 sec, after complete removal of voltage, will be suitable for a majority of these applications.

Oil Circuit Breakers and Mechanisms. Although oil circuit breakers are used in a very large portion of a-c reclosing equipments, nevertheless air circuit breakers have been used in this manner, principally on low voltage circuits. The general features mentioned in this paper in connection with oil circuit breakers apply equally as well to air circuit breakers.

Oil circuit breakers and mechanisms are available having minimum operating times (from energizing the trip coil to closing the breaker contacts) in the order of 30 to 80 cycles, on a 60-cycle basis, depending on the type and rating of the oil circuit breaker

Table I—Oil Circuit Breakers—Proposed Duty Cycles and Interrupting Ratings

No. of Groups	Total Number of Operating Cycles	Per Cent of Standard Ratings				
	Successive OCO Operations With 15-Sec Interval	0 to 5,000 Amp	5,001 to 10,000 Amp	10,001 to 20,000 Amp	20,001 to 40,000 Amp	40,001 and Above
	2	100	100	100	100	100
	4	95	95	90	85	80
	8	85	80	70	55	50
	16	75	65	50	35	
Groups of 2 OCO Operations 0 time between operations 2-min interval between groups						
1	2	90	85	75	65	60
2	4	80	75	60	45	
4	8	70	65	50	35	
8	16	60	55	40	25	
Groups of 4 OCO Operations with 0-15-60-sec time intervals. Two-min interval between groups						
1	4	85	80	65	50	
2	8	75	70	55	40	
4	16	65	60	45	30	

Fig. 1. Reclosing relay modified to permit immediate initial reclosure, showing contacts in the latched position

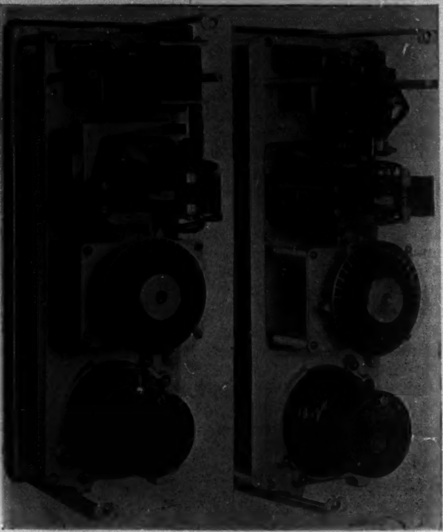

Fig. 2 (left). Reclosing relay available with provision for immediate initial reclosure showing front contact (for reclosing) and second contact (motor circuit) latched and ready for immediate operation

Fig. 3 (right). Reclosing relay without provision for immediate initial reclosure

and the form of mechanism. Generally speaking, the shorter times are obtained in connection with breakers of lower voltage ratings operating by solenoid mechanisms.

In Table I there is given a group of duty cycles and interrupting ratings, for use with oil circuit breakers, as proposed by a Joint Committee of the Edison Electric Institute, Association of Edison Illuminating Companies and the National Electric Manufacturers Association. This table includes a variety of reclosing cycles; it is evident that the trend is toward sanctioning higher interrupting duties for reclosing service. A comparison between this and similar data in use for the past 5 or 10 years will readily indicate this feature. It will be evident that suitable consideration has been given to the immediate initial reclosure, which has been incorporated in over 60 per cent of the duty cycles.

Those operating companies who have applied the immediate initial reclosure followed by 1 or 2 time delay reclosures report that the maintenance on the oil circuit breaker was not greater than that required where time delay reclosures were used throughout.

Due to the fact that trip free mechanisms utilize a latch that must reset before the closing force is applied to the breaker, it is necessary to make certain that the latch has reset before the closing effort is applied. Most available mechanisms of this type require a latch checking function. A time delay device can be used for this purpose, but such a device must have a setting long enough to take care of the various limiting conditions, such as those due to seasonal variations, and variations in operating voltage, thereby preventing the minimum time from being obtained under the more advantageous conditions. A switch in the reclosing circuit and actuated by the latching mechanism allows the shortest delay and is independent of temperature or operating voltage. This switch is adjusted to make its contact as late in the latch resetting motion as is consistent with dependable operation, and usually is connected (as shown in Fig. 4) so that its time of operation parallels that of the reclosing device. In this way the times are not additive, but are determined by the longer of the two, which usually is that of the latching mechanism. Trip free mechanisms incorporating latches with suitable resetting speeds, do not require the latch checking function.

Protective Relay Considerations. In the application of immediate initial reclosure, consideration must be given to the protective relay system. First, circuit closing protective relays must open their tripping contacts, with some safety factor, during the deenergized period. Most overcurrent relays of recent manufacture readily will meet this requirement. Some of the older types which require a comparatively long time to reset, can be modified readily to give the desired quick-resetting feature.

The selectivity of the relay system must not be upset in the case of immediate reclosure on a persisting fault. In the circuits under consideration, selectivity is obtained mostly by time differentials. The time interval between cascaded relays must be long enough to permit 2 operations, in rapid succession, of the breaker feeding directly into the fault, without the unnecessary tripping of other breakers. In many cases the protective relay has to be selective with respect to high tension transformer fuses. Applications of this type require careful coördination between the relay and transformer fuse characteristics.

As a conservative guide the spacing between successive relay times should be at least twice the time required for the breaker to clear after the trip coil is energized. The actual interval used may be reduced, depending on the length of time the circuit is open and the speed with which the relays reset. A tabulation of existing practice would be a valuable guide to operators intending to install equipment incorporating immediate initial reclosure.

RECLOSING DEVICES AVAILABLE

There are several solutions of the various problems that enter into the design and application of a-c reclosing devices. Some of the available devices have common characteristics, while others differ quite radically. In the following paragraphs there is included a brief description of a group of devices that are available for this class of service. Each of these devices has certain limits of application, as indicated in the text, and the group as a whole should be considered as being typical or representative of their class of control devices.

The electrically operated devices available for producing the required reclosing impulses, while naturally differing in detail, consist of the following elements: release mechanism; timing mechanims; contacting mechanism; antipump means; and lock-out means.

When conditions on the feeder circuit are normal and no operation of the device is required, the recloser is held in its so-called normal position (ready to operate) either by a mechanical stop or by an open contact in its operating circuit. The closing of a "b" auxiliary switch on the circuit breaker, energizes the release mechanism, thereby placing the recloser in operation.

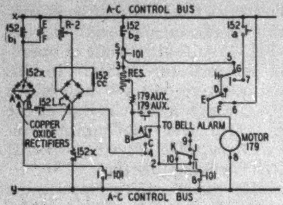

Fig. 4. Circuit for immediate initial reclosure (a-c control). Devices shown in position following opening of oil circuit breaker but prior to immediate reclosure

When breaker trips 152 b-2 closes, energizing 179 auxiliary ("antipump" or "set-up" relay) releasing *BA* and *ED* and closing *BC* and *EF;* 179 auxiliary closes and seals itself in. *BC* in closing completes circuit to 152-*X* and its rectifier, through latch—checking switch. Then 152-*X* picks up, energizing 152 closing coil through its rectifier. *EF* in closing seals motor circuit to *X*

The timing mechanism ordinarily consists of a motor driving a contacting mechanism through a suitable gear train. The contacting mechanism usually consists of 2 sequentially operated contacts—the first closing the circuit to the "set-up" or "antipump" relay which seals itself in through the "*b*" switch—the second contact completes the closing circuit of the breaker through the set-up relay contacts. Provision is made for a maximum of 3 reclosures with the time between operations individually adjustable.

The closing of the oil circuit breaker, following the operation described for the timing mechanism, releases the set-up relay. In this way "pumping" of the breaker is prevented as the sequential operation of the contacts must be repeated before another closing impulse can be given.

The lock-out means stops the recloser after the third successive operation if the breaker fails to remain closed. The recloser may be arranged to be reset to normal by hand or it may be arranged to reset itself automatically by the subsequent reclosure of the breaker.

In general, with the reclosing equipments, the control switch associated with the circuit breaker should have extra contacts for preventing operation of the recloser when the circuit is being controlled manually.

(*1*) *Modifications in Existing Reclosers Giving Immediate Initial and Subsequent Time Delay Reclosures.* Most of the reclosers furnished until recently could be adjusted for a minimum delay of 1 to 3 sec for the initial operation; usually this is not fast enough where immediate reclosure is desired. Some early reclosers can be modified so as to be suitable for immediate reclosing duty. In one case, the first of the sequentially operated contacts is latched closed at the normal position. With this arrangement the opening of the breaker through its "b" switch immediately energizes both the release and the antipump relay. The release magnet starts the timer and simultaneously the contact latch is released, permitting the closing circuit to be made. The arrangement is such that immediate initial reclosure may be used or not, as desired. Details of the construction are shown in Fig. 1.

(*2*) *Modern Reclosers With or Without Immediate Initial Reclosure and Subsequent Time Delay Reclosures.* A more modern recloser available to give immediate reclosing or not, as desired, is shown in Fig. 2. A modification which only permits reclosing after approximately 1 sec is shown in Fig. 3. In both of these motor-driven devices, normal and lock-out positions are determined by cam-operated contacts, which transfer the motor circuit to auxiliary switches on the breaker, at proper points in the reclosing cycle.

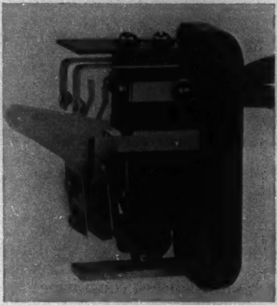

Fig. 5. Relay for 1 immediate reclosure (for attended stations) shown in normal latched position

In the normal position, the recloser motor circuit is complete except at the breaker "b" switch. As soon as the breaker opens, the "b" switch closes (see Fig. 4) and starts the device, transferring this circuit direct to the supply. Near the lock-out point the motor circuit is transferred from direct supply to a connection through an "a" switch. If the breaker is in the closed position, the recloser continues to the normal position at which point the motor circuit is transferred up to the "b" switch and stops in the normal position, ready for another reclosing cycle. When the breaker remains open, the recloser stops in the lock-out position and remains there until the breaker is reclosed.

In the immediate reclosing form, the motor control contacts are latched closed on *DE* and the reclosing contacts on *AB*, as shown in Fig. 4. When the release coil (179 auxiliary) is energized, the latch is broken and contacts *EF* close connecting the motor directly to the line. Simultaneously, contacts *BC* close, energizing the breaker control relay. The mechanism is so arranged that the immediate reclosure may be changed to time delay simply by the adjustment of the contact arms.

(3) *One Shot (Immediate) Recloser for Attended Stations.* In stations where operators are available, a great improvement in service is possible by applying a recloser for 1 operation and leaving resetting and subsequent reclosing to the operator.

A simple and inexpensive relay giving 1 immediate reclosing impulse is shown in Fig. 5, which also shows the relay held by its latch in its normal position, with both contacts open. The closing of the breaker "b" switch energizes the reclosing relay coil and the armature picks up to close the contacts, which in turn close the breaker. At the same time the relay latch is released. When the breaker closes, its "b" switch opens and the reclosing relay armature falls to the fully open position. From this point it cannot be picked up electrically, but must be returned by hand to its normal position, thus providing the required anti-pump feature. In the fully open position a second set of contacts is closed, which may be used to energize a signal calling the operator's attention to the fact that further operation is in his hands.

(4) *Mercury Reclosing Device.* A reclosing device actuated directly by the circuit breaker mechanism, giving 1, 2, or 3 reclosures at fixed time intervals, is shown in Fig. 6. The contacts and timing element are embodied in a hermetically sealed tube containing mercury. The flow of the mercury through fixed orifices, in the various chambers, provides the desired intervals between reclosures, as well as the time required for resetting. These intervals are independent of each other.

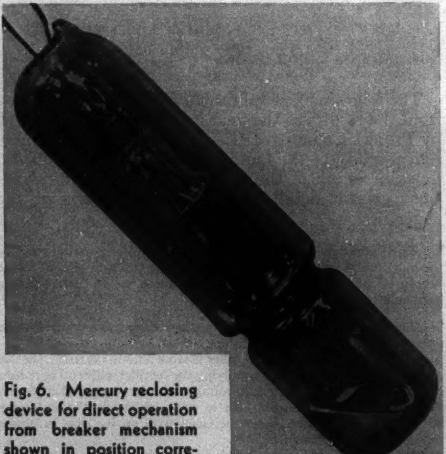

Fig. 6. Mercury reclosing device for direct operation from breaker mechanism shown in position corresponding to closed breaker

When the breaker opens, the tube is rotated to a vertical position, where contact is made, after sufficient mercury flows into the contact chamber from the initial chamber (lower end Fig. 6) thus reclosing the breaker. When the breaker recloses, the tube is returned to its original position and the mercury in the contact chamber is emptied quickly into the lock-out chamber (outer and upper chamber Fig. 6). After a predetermined number of successive operations, within a prescribed time, the mercury is all accumulated in the lock-out chamber, leaving none with which to make contact, and the breaker is locked out. If the breaker remains in the closed position for a sufficient length of time, the mercury is returned through the resetting orifice, to the initial chamber.

The "timing" orifice can be enlarged so as to give 1 reclosing operation within 30 to 60 cycles. A number of tubes can be grouped together so as to give different timing intervals between reclosures.

Table II

Type of Device Numbers in Parenthesis Refer to Corresponding Paragraphs	Fig. No.	Minimum Time From Energizing Recloser to Closing of Breaker Control Circuit, in Cycles, on a 60-Cycle Basis	Breaker Operating Cycle: OCO 15 sec OCO (2 or 4 operating cycles)	Breaker Operating Cycle: OCO 0 sec OCO	Breaker Operating Cycle: OCO 0 sec OCO 15 sec OCO 60 sec OCO	Remarks
Motor-driven (1)	1	6	x	x	x	Existing reclosers of this general design may be modified for immediate initial reclosure.
Motor-driven (2)	2	6	x	x	x	Can be adjusted for immediate initial or for time delay reclosures throughout.
Motor-driven (2)	3	40–60	x	x	x	Minimum reclosing interval 40–60 cycles.
One-shot recloser (3)	5	4	*	x	*	Simple and compact electrically operated device for obtaining 1 immediate reclosure, for attended stations. Manually reset.
Mercury reclosing device (4)	6	30–60	x	x	†	Simple and compact mechanically operated device giving a number of equally timed reclosures or 1 reclosure of 30–60 cycle interval

x available
* not available
† requires 3 elements

In Table II there is given a brief résumé of the essential characteristics of the group of reclosers, described in this paper, particularly in relation to a few of the proposed duty cycles (given in Table IV) that are typical of the automatic reclosing sequences.

The author desires to acknowledge the assistance given by L. F. Kennedy of the General Electric Company, Philadelphia works, in the preparation of this paper, particularly that section devoted to protecting and reclosing relays; and also the use of certain valuable data contained in 3 N.E.L.A. electrical apparatus committee reports (issued in 1931 and 1932), together with subsequent data relating to operating experience with a-c reclosing equipment prepared by J. T. Logan of the Georgia Power Company.

Effects of Rectifiers on System Wave Shape

Operation of mercury arc rectifiers generally results in increased harmonic currents in the rectifier supply circuits and may result in increased harmonic voltages. While these harmonics usually are not serious from the standpoint of the power system, they may result in interference to communication circuits exposed to the power circuits. This paper presents a method of computing these harmonic voltages and currents, and discusses methods of coördinating telephone systems and a-c power systems supplying rectifiers.

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AN INHERENT characteristic of the mercury arc rectifier is that the wave form of the current it draws when connected to an a-c source is distorted in character even though the wave form of the supply voltage is sinusoidal. The degree to which this distorted current may react upon the voltage wave shape of the supply system depends upon the size of the rectifier and the impedance at harmonic frequencies of the supply system. Where the distortion of the system voltage wave form by the rectifier is important, harmonic voltages and currents may appear on power circuits in addition to that supplying the rectifier, and, under certain conditions, the resulting wave shape disturbance may be widespread in character.

The harmonic voltages and currents introduced by a rectifier are usually not serious from the standpoint of the operation of the power system. In several cases that have arisen during the past few years, however, these components have resulted in noise interference arising by induction in telephone circuits involved in exposures with the power system. The increasing use of the rectifier as a source of supply for d-c traction systems and its further application in connection with high powered radio transmitting equipment have made the problem of inductive coördination between telephone circuits and power systems supplying rectifiers one of increasing importance. Project Committee 1C on Wave Shape of the Joint Subcommittee on Development and Research[*] of the National Electric Light Association and Bell Telephone System has conducted an investigation of the effects of rectifiers on supply system wave shape. The present paper is based to a considerable extent upon the results of that investigation.

This paper presents a method, employing equivalent circuits and empirical formulas, that has been developed for computing the harmonic voltages and currents to be expected from a rectifier installation, discusses the various factors influencing the problem, and considers methods of coördinating telephone systems and a-c power systems supplying rectifiers. The use of the empirical formulas for estimating the magnitudes of the harmonic components to be expected from a rectifier requires a knowledge of the impedance at harmonic frequencies of the supply system involved. This paper also describes a method of estimating this impedance from the physical dimensions of the lines and name plate data on the associated apparatus. The theoretical information presented is supported by considerable data representing the results of field studies arranged to check the accuracy of the empirical formulas in connection with operating rectifier installations.

In this paper only the usual type of polyphase rectifier operating without control grids is considered.

SUMMARY OF CONCLUSIONS

The following general conclusions have been drawn from the results of the field investigations conducted by Project Committee 1C and a supplementary theoretical study of the factors influencing this problem. Certain results of the study are discussed in somewhat greater detail in subsequent portions of the paper.

1. The operation of a rectifier generally results in an increase in the magnitudes of the *odd nontriple* harmonic currents present in the supply circuit, and may result in an increase in the corresponding harmonic voltages.

2. The magnitudes of these harmonic components depend upon several factors including:
Supply Circuit Voltage. If all other factors remain the same, the use of a higher voltage feeder for supplying the rectifier will tend to reduce the magnitudes of the harmonic voltages and currents on that feeder.
Power Supplied to Rectifier. In a given situation the inductive influence of the supply feeder increases with an increase in power supplied to the rectifier.
Supply System Impedance. Within certain limits the voltage wave-shape distortion increases with an increase in the power system impedance at harmonic frequencies, while the distortion of the current wave form tends to decrease. Under certain conditions this effect is reflected in less voltage wave shape distortion on under-

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Full text of a paper recommended for publication by the A.I.E.E. committees on (1) electrical machinery, (2) communication, and (3) power transmission and distribution; and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 14, 1933; released for publication Nov. 22, 1933. *Not published in pamphlet form.*

[*] As discussed in a "Symposium on Coördination of Power and Telephone Plant" presented at the winter convention of the A.I.E.E. in 1931 (A.I.E.E. TRANS., v. 50, 1931, p. 437–74) the Joint Subcommittee on Development and Research was established by the N.E.L.A. and the Bell Telephone System in 1923 as an agency for carrying out technical work on mutual problems of inductive coördination. Participation of the electric light and power industry in the activities of this subcommittee now is being continued under the sponsorship of the Edison Electric Institute.

ground cable circuits than on overhead lines for a given rectifier load and supply system voltage.

Number of Rectifier Phases. The distortion of both the current and voltage wave shape is less for 12-phase rectifiers than for 6-phase rectifiers. In the cases investigated by the committee, 12-phase operation resulted in an average reduction in the current and voltage telephone interference factors (T.I.F.'s)[1] on the supply circuit of approximately 50 per cent, compared with 6-phase operation in the same location.

3. In certain cases, the operation of a rectifier may increase the inductive influence of considerable portions of the power system, in addition to the particular circuit supplying the rectifier.

4. An empirical method has been developed for estimating the approximate magnitudes of the harmonic voltages and currents in the supply circuit to a rectifier in terms of the fundamental frequency voltage and current, the order of the harmonic component in question, and the impedance at harmonic frequencies of the supply system. The results of the field measurements indicate that this method gives reasonably accurate results over a wide range of conditions.

5. In the present state of the art, there is no single, universally applicable method of coördinating telephone systems and a-c power systems supplying rectifiers. In a particular situation, a study of the conditions will indicate which of the various methods of coördination available for use in the power or telephone systems will meet best the service requirements of both these systems in the most convenient and economical manner. Two of the methods relating particularly to the control of the influence of rectifier supply circuits are described in some detail in this paper. Measures relating to other phases of the control of influence, coupling, and susceptiveness which should be considered in the solution of a given problem are treated in various publications of the joint subcommittee on development and research.

METHOD OF ESTIMATING MAGNITUDES OF HARMONIC CURRENTS AND VOLTAGES

The wave shape of the current in the supply circuit to a rectifier under light-load conditions or for the ideal case of a source of supply without reactance has been analyzed by a number of authors.[2,3] Under load conditions, in the practical case in which supply system reactance is appreciable, this wave shape may be modified considerably and different methods have been proposed for estimating the wave shape under these conditions. One of these[4] involves the extension of the light-load formula along theoretical lines. The method worked out by Project Committee 1C makes use of empirical formulas developed from a theoretical study of the factors influencing the problem. The empirical constants employed were determined from the results of actual measurements of the harmonic currents and voltages in the supply circuits to a number of rectifiers.

CURRENT WAVE SHAPES

Ideal Case, No Supply System Reactance. As a preliminary step in the development of the equivalent circuit and empirical formulas for the practical case, it is helpful to consider first the ideal case, not approached in practice, in which a rectifier is supplied from a system of negligible reactance through a transformer of negligible leakage reactance.

Figure 1 illustrates the theoretical or light-load wave shapes of the currents in the a-c supply circuits to 3 rectifier arrangements frequently used in practice. Cases 1 and 2, as indicated in the schematic diagrams, apply to common types of 6-phase rectifiers while case 3 illustrates a transformer arrangement often employed with 12-phase rectifiers. The manner in which these current wave shapes arise has been treated thoroughly in texts on the subject[2,3] and will not be analyzed here.

The so-called 3-phase full-wave rectifier is equivalent in its operation to a 6-phase rectifier and, therefore, the conclusions drawn in this paper for the latter hold equally well for the former.

The current wave illustrated in case 1 may be resolved readily into a Fourier series consisting of a fundamental component and harmonics of orders $6S \pm 1$ where S is any positive whole number—namely, harmonics of orders 5, 7, 11, 13, 17, 19, 23, 25, etc. In each case the magnitude of the nth harmonic component is equal to $1/n$ times the fundamental current. The current wave illustrated in case 2 may be resolved into a similar series, the harmonics differing from those in case 1 in phase only.

The current wave of the 12-phase rectifier may be resolved similarly into a Fourier series consisting of a fundamental component and harmonics of orders $12S \pm 1$ where S is any positive whole number—namely, harmonics of orders 11, 13, 23, 25, etc. As in the case of the 6-phase rectifier the mag-

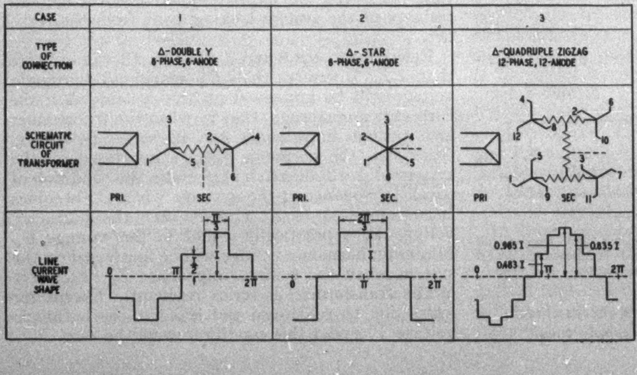

Fig. 1. Theoretical wave shape of input current to a rectifier operating on a supply circuit of negligible reactance

Overlapping effects and transformer magnetizing current neglected; rectifier output circuit assumed to be inductive. I = rectified direct current

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1. For all numbered references, see list at end of paper.

nitude of the nth harmonic is equal to $1/n$ times the fundamental component. It may be noted that harmonics of orders 5, 7, 17, 19, etc., which were present in the case of the 6-phase rectifier are not, theoretically, present in the 12-phase arrangement.

Figure 2A illustrates an equivalent phase-to-neutral circuit that represents the ideal case of no supply system reactance. If n represents the order of any harmonic that may be present and I_{no} represents the harmonic current in the ideal case at that frequency, from the foregoing analysis

$$I_{no} = \frac{I_\phi}{n} \tag{1}$$

where I_ϕ represents the fundamental frequency line current.

In Fig. 2A, R_o is a fictitious quantity representing the internal resistance of the rectifier and E_n represents the harmonic voltage that will produce a current I_n in a circuit of impedance R_o (since the external impedance, that of the supply circuit and transformer, has been assumed negligible in this case). Then E_n is considered as the "open-circuit" harmonic voltage generated by the rectifier and

$$E_n = I_{no}R_o \tag{2}$$

Measurements on a comparatively large number of rectifiers indicate that the magnitude of the so-called internal resistance is approximately

$$R_o = \frac{V_{\phi-N}}{3I_\phi} \tag{3}$$

where $V_{\phi-N}$ represents the fundamental frequency phase-to-neutral voltage.

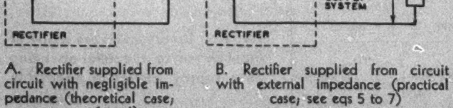
Substituting eqs 1 and 3 in eq 2, the magnitude of the "generated voltage" E_n becomes

$$E_n = \frac{V_{\phi-N}}{3n} \tag{4}$$

Practical Case. An equivalent circuit for the practical case taking into account the modification of the current wave shape by the supply system reactance may be set up now by merely adding to the circuit for the ideal case elements representing the impedance of the supply system and the leakage impedance of the rectifier transformer. An equivalent circuit so modified is illustrated in Fig. 2B. In this revised circuit,

$$I_n = \frac{E_n}{\sqrt{R_o^2 + Z_n^2}} \tag{5}$$

where Z_n represents the vector sum of the transformer leakage impedance (Z_{tn}) and the system phase-to-neutral impedance (Z_{sn}) at the harmonic frequency, both referred to the fundamental frequency voltage $V_{\phi-N}$.



A. Rectifier supplied from circuit with negligible impedance (theoretical case; see eqs 1 to 4)

B. Rectifier supplied from circuit with external impedance (practical case; see eqs 5 to 7)

Fig. 2. Phase-to-neutral equivalent circuits of rectifiers for calculating harmonics in supply circuit

Substituting eq 4 in eq 5

$$I_n = \frac{V_{\phi-N}}{3n\sqrt{R_o^2 + Z_n^2}} \tag{6}$$

It may be noted from eq 6 that, in order to compute the magnitude of any harmonic current component, it is necessary to know: (1) fundamental frequency voltage $V_{\phi-N}$, (2) the fundamental frequency current (see eq 3), and (3) the combined impedance at the harmonic frequency of the rectifier transformer and the supply system.

An examination of eq 6 and the equivalent circuit (Fig. 2B) indicates that the maximum current at any harmonic frequency will obtain when a condition of resonance exists between the transformer leakage reactance and the system reactance. Under this condition the term Z_n becomes small compared to R_o and the harmonic current approaches that which would obtain in the ideal case of no supply circuit reactance. Under this condition, from eq 1

$$I_n = \frac{I_\phi}{n}$$

Conversely, the harmonic current is minimum at any frequency when there is a condition of parallel resonance in the system impedance. Under this condition the term Z_n becomes relatively large compared to R_o. If it were not for losses due to resistance and leakage in the system, the system impedance at parallel resonance would be infinite and the harmonic current at that frequency would be zero.

VOLTAGE WAVE SHAPE

Referring again to Fig. 2B, the phase-to-neutral harmonic voltage on the supply circuit at the line terminals of the rectifier transformer is

$$V_n = I_nZ_{sn} \tag{7}$$

The phase-to-neutral harmonic voltage at any other point on the system may be computed in a similar manner from the product of the harmonic current at that point and the phase-to-neutral harmonic impedance of the system looking away from the rectifier.

Reference to eqs 6 and 7 and Fig. 2B will indicate that if Z_{sn} is greater than R_o, maximum harmonic voltage will be impressed on the system when the current is a maximum, that is, when the transformer and system impedances are in series resonance. Otherwise, the harmonic voltage impressed on the system (V_n) will be maximum under the condition of parallel resonance of the system, when Z_{sn} becomes large compared to Z_{tn} and R_o and the harmonic voltage V_n is practically equal to the voltage E_n. Minimum harmonic voltage will be impressed on the system when the system impedance Z_{sn}, exclusive of the transformer, is series resonant. Except for losses due to resistance and leakage, the harmonic voltage V_n under this condition would be zero.

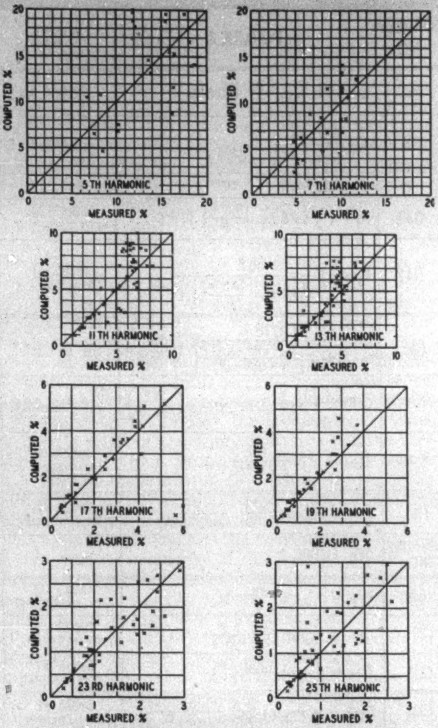


Fig. 3. Comparison of harmonic currents computed by empirical method with measured values

APPLICATION OF FORMULAS TO 12-PHASE RECTIFIERS

In the discussion of the ideal case of no supply circuit reactance it was brought out that, theoretically, harmonics of orders 5, 7, 17, 19, etc., are not present in the input circuit of a 12-phase rectifier. In practice, however, presumably due to unbalances between the 2 6-phase units that make up a 12-phase rectifier, these components are not reduced to zero. While their relative magnitudes have been found to vary with different rectifier installations, experience indicates that on an average these theoretically suppressed components appear in magnitudes approximately equal to $^1/_5$ those that would result from 6-phase rectifiers. The empirical formulas (eqs 6 and 7) therefore, may be modified for application to 12-phase rectifiers as follows:

$$I_n = \frac{K V_{\phi - N}}{3n\sqrt{R_e^2 + Z_n^2}} \tag{8}$$

$$V_n = I_n Z_{sn} \tag{9}$$

For 6-phase rectifiers, $K = 1$. For 12-phase rectifiers, $K = 1$ for $n = 11, 13, 23, 25$, etc.; $K = 0.2$ for $n = 5, 7, 17, 19$, etc.

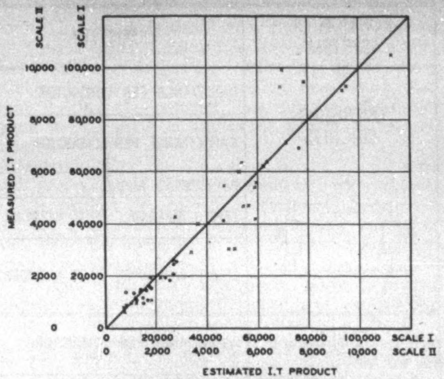


Fig. 4. Comparison of I.T products estimated by empirical method with those measured on circuits supplying rectifiers

o = scale I; x = scale II

ACCURACY OF EMPIRICAL FORMULAS

The accuracy of the foregoing formulas depends upon the accuracy of the assumption that E_n is a fixed and constant voltage and the degree to which the quantity R_e is represented correctly by eq 3. The accuracy of results obtained by the formula also depends upon the precision to which the system impedance is known. Project Committee 1C has carried out a rather extensive series of calculations and measurements to check the over-all accuracy of the method.

The correlation between calculated and measured values of the individual harmonic currents in the various cases tested is indicated in Fig. 3. In order to demonstrate the accuracy of the formula itself, the calculations are based upon measured, rather than calculated, system impedances. It may be noted that the greatest spread between measured and computed values was found in the case of the 5th harmonic. This can be explained in part by the presence of 5th harmonic components from sources on the system other than the rectifier which affected the measured values, but which were not considered in the computations. This effect is probably also present, but to a less marked degree, at the other harmonic frequencies. In general it appears that in a large majority of cases the individual harmonic components can be computed to within ±30 per cent. In view of the nature of the quantities being computed, which are often highly variable in character due to rectifier load fluctuations, the method is considered sufficiently accurate for all practical purposes.

In inductive coördination studies a weighted combination of the various harmonic components present added in accordance with the root-sum-square method and called the "telephone interference factor" or T.I.F.[1] is usually of greater interest than the magnitudes of the individual harmonics. The phase

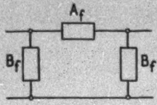
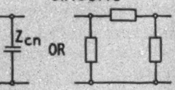
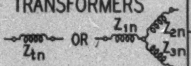
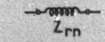
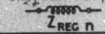
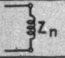
PORTION OF SYSTEM	QUANTITY	FORMULA NO.	FORMULA	UNITS
OVERHEAD CIRCUITS 	INDUCTANCE PER CONDUCTOR	(10)	$L = 0.741 \log_{10} \frac{D}{r} + 0.080$	MH. PER MILE
	CAPACITANCE PER CONDUCTOR	(11)	$C = \frac{0.0388}{\log_{10} \frac{D}{r}}$	µF. PER MILE
	HYPERBOLIC ANGLE	(12)	$\theta = 6.28 \ell \sqrt{0.1 LC}\ 10^{-4} f$	RADIANS
	SERIES IMPEDANCE OF π NETWORK	(13)	$A_f = +j\, 6.28 \ell L \left[\frac{\text{SIN}\,\theta}{\theta}\right] 10^{-3} f$	OHMS AT FREQUENCY f
	SHUNT IMPEDANCE OF π NETWORK	(14)	$B_f = -j \frac{10^6}{3.14 \ell C \left[\frac{\text{TAN}\,\theta/2}{\theta/2}\right] f}$	OHMS AT FREQUENCY f
CABLE CIRCUITS 	CAPACITANCE PER CONDUCTOR, 3-PHASE BELTED CABLE	(15)	$C = \frac{0.0776\ K}{\log_{10}\left[\frac{3a^2(R^2-a^2)^3}{r^2(R^6-a^6)}\right]}$ (SEE FIG. 8)	µF. PER MILE
	CAPACITANCE PER CONDUCTOR, 3-PHASE SHIELDED OR 1-PHASE CABLE	(16)	$C = \frac{0.0388\ K}{\log_{10}\left(\frac{R}{r}\right)}$ (SEE FIG. 8)	µF PER MILE
	EQUIVALENT SHUNT IMPEDANCE (FOR π NETWORK USE FORMULAS 13 & 14	(17)	$Z_{cn} = -j \frac{10^6}{6.28 f \ell C}$	OHMS AT FREQUENCY f
TRANSFORMERS 	EQUIVALENT SERIES IMPEDANCE TWO-WINDING TRANSFORMER	(18)	$Z_{tn} = +j(n) \frac{\%X}{100} \frac{V^2}{1000\,(KVA)}$	OHMS AT n^{TH} HARMONIC,
	EQUIVALENT CIRCUIT THREE WINDING TRANSFORMER	(19)-(28) INCL	SEE FIGURE 9	
CURRENT LIMITING REACTORS 	EQUIVALENT SERIES IMPEDANCE	(29)	$Z_{rn} = +j(n) \frac{V_R}{I}$	OHMS AT n^{TH} HARMONIC
	EQUIVALENT SERIES IMPEDANCE	(30)	$Z_{rn} = +j(n) \frac{\%X}{100} \frac{V}{\sqrt{3}\,I}$	OHMS AT n^{TH} HARMONIC
	EQUIVALENT SERIES IMPEDANCE	(31)	$Z_{rn} = +j(n) \frac{1000\ KVA}{I^2}$	OHMS AT n^{TH} HARMONIC
INDUCTION VOLTAGE REGULATORS 	EQUIVALENT SERIES IMPEDANCE 3-PHASE REGULATOR	(32)	$Z_{REG\,n} = +j(n) \frac{\%X}{100} \frac{(1000)(KVA)}{3 I^2}$	OHMS AT n^{TH} HARMONIC
	EQUIVALENT SERIES IMPEDANCE SINGLE-PHASE REGULATOR	(33)	$Z_{REG\,n} = +j(n) \frac{\%X}{100} \frac{(1000)(KVA)_1}{I^2}$	OHMS AT n^{TH} HARMONIC
ROTATING MACHINERY 	EQUIVALENT SHUNT IMPEDANCE	(34)	$Z_n = +j(n) \frac{\%X}{100} \frac{V^2}{1000\,(KVA)}$	OHMS AT n^{TH} HARMONIC

Fig. 5. Equivalent circuits of various portions of a power system, and formulas for calculating their phase-to-neutral impedances at harmonic frequencies

a = Cable dimension (inches) (see Fig. 8)
A_f = Series impedance of equivalent π network
B_f = Shunt impedance of equivalent π network
C = Capacitance to neutral per conductor per mile (microfarads)
D = Mean spacing of conductors (inches) $D = \sqrt[3]{D_{12} D_{23} D_{31}}$
f = Frequency (cycles per second)
I = Rated full-load current per phase (amperes)
K = Specific inductive capacity of cable insulation (see Fig. 8)
KVA = 3-Phase rating (kilovoltamperes)
KVA_1 = Single-phase rating (kilovoltamperes)
L = Inductance per conductor per mile (milhenries)
= Length of line (miles)

n = Order of harmonic
$\%X$ = Reactance expressed in per cent
R = Cable dimension (inches) (see Fig. 8)
r = Radius of conductor (inches)
$\frac{\text{Sin}\,\theta}{\theta}$ = Correction factor (see Fig. 6)
$\frac{\text{Tan}\,\theta/2}{\theta/2}$ = Correction factor (see Fig. 7)
V = Rated phase-to-phase voltage (volts)
V_r = Reactive voltage drop across reactor (volts)
θ = Hyperbolic angle of circuit (radians)

current multiplied by its telephone interference factor (I.T) frequently is used as an index of the inductive influence of a power circuit from the standpoint of induction from balanced currents. The correlation between the measured and computed I.T products from the cases tested by the committee is indicated in Fig. 4. Except in a few cases the computed values were within about ±20 per cent of the measured values. The accuracy of these calculations is better than that for the individual harmonics because in making the summation certain errors in the individual components tend to average out.

The accuracy of the calculation of individual harmonic voltages and the voltage T.I.F. to which they contribute depends upon the accuracy with which the system impedance at harmonic frequencies is known.

METHOD OF COMPUTING SYSTEM IMPEDANCES AT HARMONIC FREQUENCIES

Measured values of the impedance of the supply system at harmonic frequencies required in the empirical formulas discussed are seldom available. In using the formulas, therefore, it is usually necessary to estimate this impedance, at the various frequencies desired, from the physical dimensions of the lines and cables involved and the name plate data on the associated apparatus.

In making calculations of system impedance it has been found convenient to build up a composite equivalent circuit made up of elements representing the impedances of the lines and of the various pieces of connected equipment. It has been found that overhead transmission lines or cables may be represented by networks of inductive and capacitive reactances, while apparatus such as transformers, reactors, regulators, and rotating machinery can be represented approximately by inductances. When all the elements of the equivalent circuit have been assembled in their proper physical relationships, they may be combined at any desired frequency to reduce the entire network to a single impedance (Z_m) as required in the empirical formulas.

At harmonic frequencies the resistance and leakage of the various elements of the power system are ordinarily negligible compared to the inductive and capacitive reactance. However, at frequencies where series or parallel resonance occurs, the resultant impedance is determined largely by the resistance and leakage. From a practical standpoint, the error introduced in impedance calculations near points of resonance by other approximations involved is probably as important as that due to neglecting resistance or leakage. Moreover, as series or parallel resonant points in the system impedance are approached, the harmonic currents and voltages from a rectifier approach values fixed by other elements, and relatively large errors in the system impedance are not critical.

In general, the lowest impedance path to harmonics is that toward the main source of supply and the impedance of that source is, therefore, generally the controlling factor in the system impedance. Except in unusual cases the shunting effects of load equipment may be neglected. However, the shunting effects of cables or long overhead lines other than that feeding the rectifier, but supplied from the same source, may be important and must be considered.

In establishing the equivalent circuit for a system it is necessary, of course, to reduce the impedances of the various elements to a common voltage basis usually determined by the fundamental frequency voltage at the point where the harmonic components are to be calculated.

Formulas for the equivalent phase-to-neutral impedances at harmonic frequencies of various portions of a power system are summarized in Fig. 5.

Overhead Lines and Cables. It may be noted that in Fig. 5 the complete equivalent circuit for an overhead line or cable is shown in the form of a π-network. The method[5] of computing the elements of this network makes use of the hyperbolic angle θ of the line and the formulas involve the functions $\frac{\sin\theta}{\theta}$ and $\frac{\tan\theta/2}{\theta/2}$. For convenience these 2 quantities have been plotted against values of the angle θ (in radians) in Figs. 6 and 7, respectively.

Formulas for the capacitance-to-neutral (C) of a cable involve details of the cross-sectional dimensions of the cable as indicated in Fig. 8. For shorter lengths of cables (of the order of 5 miles or less) the series reactance may be neglected and the cable may be represented by a simple shunt capacitance as indicated in eq 17.

Transformers. The per cent reactances to be used in the transformer equations (18 to 28) should

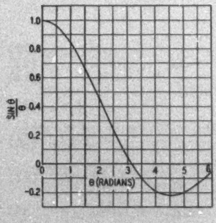


Fig. 6 (above). Curve of $\frac{\sin\theta}{\theta}$ in terms of angle θ

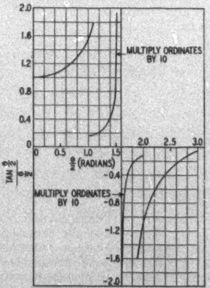
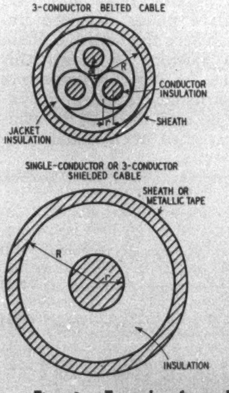


Fig. 7 (right). Curves of $\frac{\tan\theta/2}{\theta/2}$ in terms of $\frac{\theta}{2}$



$$C = \frac{0.0776\,K}{\text{Log}_{10}\left[\frac{3a^2(R^2-a^2)^3}{r^2(R^6-a^6)}\right]}\ \mu\text{f per mile}$$

R = Distance from center of cable to sheath

a = Distance from center of cable to center of conductor

$$C = \frac{0.0388\,K}{\text{Log}_{10}\left(\frac{R}{r}\right)}\ \mu\text{f per mile}$$

(For shielded cable, R is the distance from center of conductor to metallic tape around conductor insulation)

Fig. 8. Formulas for calculating phase-to-neutral capacitance of power cables

Approximate values of specific inductive capacity (K)

Impregnated paper (solid) = 3.7
Impregnated paper (oil filled) = 3.5
Rubber = 6.0
Varnished cloth = 4.5

Formulas from "Principles of Electric Power Transmission and Distribution," by Woodruff, John Wiley and Sons, 1925, P. 56–8) be taken from the name plate of the transformer whenever possible. Where this value is not available, the following approximate percentages, based upon experience, have been found suitable for use in preliminary estimates:

Rectifier transformers	4%
Distribution transformers	3%
Power transformers for primary voltages up to 33 kv	6%
Power transformers for primary voltages above 33 kv	10%

Formulas for the equivalent circuit of a 3-winding transformer are given, together with a schematic circuit diagram, in Fig. 9. It may be noted that the reactances in Fig. 9 are at the fundamental frequency. The corresponding impedances at the frequency of the *n*th harmonic, therefore, would be obtained by multiplying these quantities by *n*. For example:

$$Z_{1n} = +jn(X_1) \qquad (28)$$

Induction Voltage Regulators. The results of measurements at harmonic frequencies of the impedance and ratio characteristics of induction voltage regulators indicate that these devices may be considered equivalent to variable ratio autotransformers the leakage reactance of which varies with regulator setting. In view of this variation in impedance, it is generally necessary to use an average value in system impedance estimates. Measurements on a limited number of regulators indicate that this reactance averages about 18 per cent, based upon the regulator rating, for either 3-phase or single-phase regulators.

Rotating Machinery. Since very little information has been available heretofore on the reactance of rotating machinery to impressed harmonics, project committee 1C conducted measurements in the field on 49 machines, the results being as shown in Table I.

The results of the tests indicated a fairly consistent relationship between the impedance to impressed harmonics and the negative phase sequence impedance of the machine. Where the negative phase sequence impedance of a machine is known, this quantity multiplied by 0.9 for turbine generators and by 0.7 for hydroelectric generators and synchronous condensers may be used in eq 28 for computing the equivalent reactance at harmonic frequencies.

ILLUSTRATIVE EXAMPLE OF EQUIVALENT NETWORK

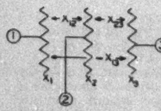
An example of the method of setting up a phase-to-neutral equivalent circuit for use in computing the impedance of a system supplying a rectifier is illustrated in Fig. 10. In the upper part of the figure is given a single-line diagram of the system; in the lower part is shown the equivalent circuit, each portion of which is numbered to correspond to the portion of the system it represents. The formula applying to each element of the circuit is indicated. It should be appreciated that this example purposely has been made complicated in order to illustrate a large number of equivalent circuits. In many cases the rectifier transformer and the circuit between the rectifier and the substation control the system impedance to harmonics.

COÖRDINATIVE MEASURES

As previously discussed, experience indicates that the inductive influence of a power circuit when supplying rectifiers may be considerably greater than when supplying the more usual types of load. Therefore, coördination of exposed telephone circuits with power circuits supplying rectifiers may be expected to be more difficult than with circuits supplying other loads. In this problem, as in all inductive coördination work, the general principle[6] of coöperative advance planning of the power and telephone system is, of course, very helpful.

In the present state of the art, the following specific coördinative methods appear to be the most promising:

1. Advance planning of method of supplying rectifier from the standpoint of minimizing wave shape distortion.
2. Frequency selective devices.
3. Coördinated power circuit transpositions.
4. Reduction of power circuit unbalances, such as those caused by single-phase branches.
5. Coördinated telephone circuit transpositions.
6. Reduction of telephone circuit unbalances, such as those caused by the connection of ringer windings from one side of line to ground for selective ringing.
7. Shielding of telephone cable circuits by grounding the cable sheath.

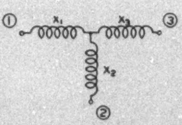


$$X_{12} = \frac{\%X_{12}}{100} \times \frac{V_1^2}{1{,}000(KVA)_{12}} \text{ (ohms)} \qquad (19)$$

$$X_{23} = \frac{\%X_{23}}{100} \times \frac{V_1^2}{1{,}000(KVA)_{23}} \text{ (ohms)} \qquad (20)$$

$$X_{13} = \frac{\%X_{13}}{100} \times \frac{V_1^2}{1{,}000(KVA)_{13}} \text{ (ohms)} \qquad (21)$$

$\% X_{12}$ = Per cent reactance between windings 1 and 2
$\% X_{23}$ = Per cent reactance between windings 2 and 3
$\% X_{13}$ = Per cent reactance between windings 1 and 3
V_1 = Rated voltage of winding 1 (phase-to-neutral)
V_2 = Rated voltage of winding 2 (phase-to-neutral)
V_3 = Rated voltage of winding 3 (phase-to-neutral)
$(KVA)_{12}$ = KVA base (per phase) for reactance rating $\% X_{12}$
$(KVA)_{23}$ = KVA base (per phase) for reactance rating $\% X_{23}$
$(KVA)_{13}$ = KVA base (per phase) for reactance rating $\% X_{13}$



$$X_{12} = X_1 + X_2 \text{ (ohms)} \qquad (22)$$

$$X_{23} = X_2 + X_3 \text{ (ohms)} \qquad (23)$$

$$X_{13} = X_1 + X_3 \text{ (ohms)} \qquad (24)$$

$$X_1 = \frac{X_{13} - X_{23} + X_{12}}{2} \text{ (ohms)} \qquad (25)$$

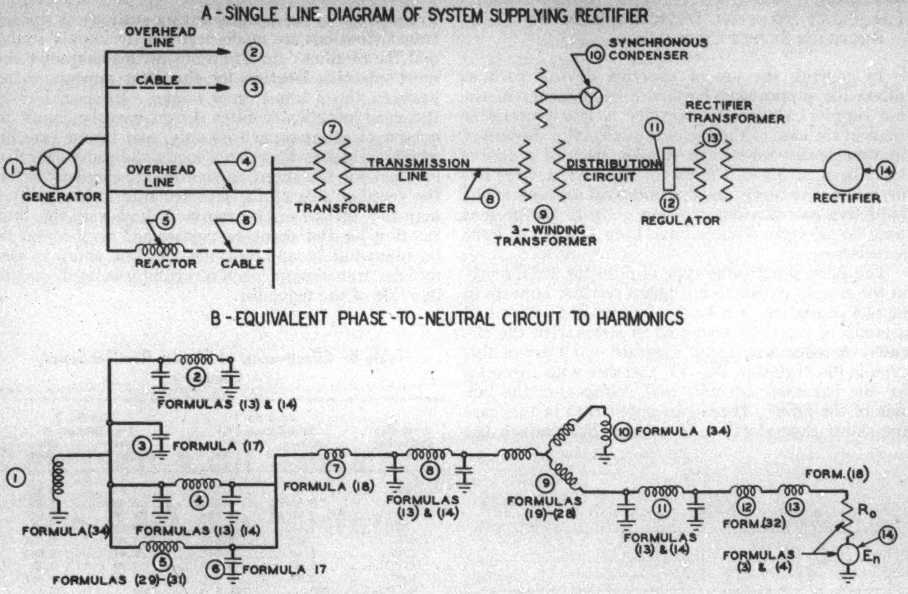
$$X_2 = \frac{X_{12} - X_{13} + X_{23}}{2} \text{ (ohms)} \qquad (26)$$

$$X_3 = \frac{X_{13} - X_{12} + X_{23}}{2} \text{ (ohms)} \qquad (27)$$

X_1 = Leakage reactance associated with winding 1
X_2 = Leakage reactance associated with winding 2
X_3 = Leakage reactance associated with winding 3
X_{12} = Total leakage reactance between windings 1 and 2
X_{23} = Total leakage reactance between windings 2 and 3
X_{13} = Total leakage reactance between windings 1and 3

Fig. 9. Equivalent circuits of 3-winding transformers

Note. All reactances must be referred to the same phase-to-neutral voltage base (here V_1); the reactances may be referred to phase-to-neutral voltage base V by multiplying each reactance by $(V/V_1)^2$


A - SINGLE LINE DIAGRAM OF SYSTEM SUPPLYING RECTIFIER

B - EQUIVALENT PHASE-TO-NEUTRAL CIRCUIT TO HARMONICS

①
GENERATOR
OVERHEAD LINE
②
CABLE
③
OVERHEAD LINE
④
REACTOR
⑤
CABLE
⑥
⑦
TRANSFORMER
TRANSMISSION LINE
⑧
⑨
3-WINDING TRANSFORMER
⑩
SYNCHRONOUS CONDENSER
DISTRIBUTION CIRCUIT
⑪
⑫
REGULATOR
RECTIFIER TRANSFORMER
⑬
RECTIFIER
⑭
FORMULAS (13) & (14)
FORMULA (17)
FORMULA(34)
FORMULAS (13) (14)
FORMULAS (29)-(31)
FORMULA 17
FORMULA (18)
FORMULAS (13) & (14)
FORMULAS (19)-(28)
FORMULA (34)
FORMULAS (13) & (14)
FORM.(32)
FORM.(18)
R_0
E_n
FORMULAS (3) & (4)

Fig. 10. Example of application of equivalent circuits and corresponding formulas

Of these methods, only the first 2 are discussed in this paper. Various engineering reports of the Joint Subcommittee on Development and Research contain information on the remaining items. These other factors, of course, should be given due consideration in any coördination study.

As shown by the diverse character of the items listed, no single method of coördination is universally applicable in all cases. A study of the various factors present in a particular situation will indicate what method, or methods, of coördination applied to the telephone system, the power system, or both will meet best the service requirements of both systems in the most convenient and economical manner.

Power System Factors Affecting Wave Shape

In many cases the distortion in supply system wave shape may be minimized by advance consideration from the coördination standpoint of the method of supplying a rectifier. Economies in the application of coördinative measures often may be realized when the following points are considered in selecting the method of supplying power to a rectifier:

1. The voltage wave shape distortion generally will be minimized when the rectifier is supplied from a power source of relatively large capacity over a short length of circuit. However, the current wave shape distortion may be important if telephone lines are exposed to this circuit.

2. Other conditions remaining the same, the higher the supply circuit voltage the less, in general, will be the distortion of both the current and voltage wave shape.

3. The distortion of the supply circuit voltage wave shape generally will be less when the rectifier is supplied from a cable network than from overhead lines.

4. The distortion of voltage wave shape on distribution circuits applied from the same transmission system as a rectifier may be an important factor. This is especially true where the distribution circuits occupy poles jointly with telephone circuits. As an approximation, the voltage T.I F. on the distribution system may be assumed equal to the voltage T.I.F. of the transmission system at the point where the distribution system is supplied. The voltage T.I.F. at any point on the transmission system may be estimated by the empirical methods previously discussed.

5. Where various methods of supplying power to a rectifier are available, a preliminary investigation of the power system impedance at harmonic frequencies will indicate the method that will cause the least distortion of the system voltage wave shape. In the cases investigated, the most desirable arrangement has been found to be that in which a relatively low impedance is seen looking away from the rectifier at points from which other circuits involved in exposures with the telephone plant are supplied.

Table I—Measured Per Cent Reactance (Referred to 60 Cycles) to System Harmonics of 60-Cycle Rotating Machinery

	Turbine Generators	Hydroelectric Generators	Synchronous Condensers
Average	11 (24)	23 (14)	21 (11)
Minimum	4.7	12	14
Maximum	17	29	35

Note: Figures in parentheses indicate number of machines included in average.

Frequency Selective Devices Applied to Rectifier Supply Circuit

In general, the use of selective devices such as filters for suppressing harmonic components in the a-c supply circuit to a rectifier is less practicable than in the case of the d-c output circuit. However, in some cases where the smaller sizes of rectifiers have been involved, the use of selective devices has been found to be the most economical solution of the inductive coördination problem. Up to the present time no selective devices have been applied to large rectifiers.

The most practicable type of filter for use directly in the supply circuit to a 6-phase rectifier appears to be one consisting of a bank of shunt capacitors and a group of reactors connected in series with the circuit. A schematic circuit diagram of a filter of this type is illustrated in Fig. 11, together with formulas for the harmonic currents and voltages on the line side of the filter. It may be noted that in this case the shunt capacitors are Δ-connected, although the same capacitor rating in kilovoltamperes would be required if they were Y-connected.

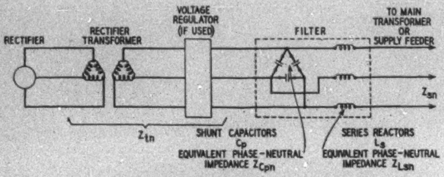

RECTIFIER
RECTIFIER TRANSFORMER
VOLTAGE REGULATOR (IF USED)
FILTER
TO MAIN TRANSFORMER OR SUPPLY FEEDER
Z_{sn}
Z_{tn}
SHUNT CAPACITORS
C_p
EQUIVALENT PHASE-NEUTRAL IMPEDANCE Z_{Cpn}
SERIES REACTORS
L_s
EQUIVALENT PHASE-NEUTRAL IMPEDANCE Z_{Lsn}

Fig. 11. Schematic diagram of a filter for improving wave shape of a-c supply to a rectifier

Harmonic current on line side of filter

$$I'_n = \frac{V_{\phi-n}}{3_n} \cdot \frac{Z_{Cpn}}{Z_{Cpn} + Z_{LSn} + Z_{Sn}} \cdot \frac{1}{\sqrt{R_o^2 + \left[Z_{tn} + \frac{Z_{Cpn}(Z_{LSn} + Z_{Sn})}{Z_{Cpn} + Z_{LSn} + Z_{Sn}}\right]^2}} \qquad (35)$$

(Impedance to be added vectorially.) Harmonic phase-to-neutral voltage

$$V'_n = I'_n Z_{Sn} \qquad (36)$$

Usually this type of filter is most effective if the shunt capacitors are connected on the line side of, and immediately adjacent to, the rectifier transformer. The most favorable location for the series reactors has been found to be on the line side of the capacitors. The values of shunt capacitance and series inductance chosen depend upon the size of the rectifier, the voltage of the circuit in which they are to be connected, the system impedance, the effectiveness desired, and the effect on fundamental frequency voltage regulation.

In one situation, a successful combination for use in the 2,300-volt supply circuit to a 200-kw rectifier associated with a 50-kw radio broadcasting station was found to be a Δ-connected bank of capacitors of 15 μf each and series reactors of 13 mh each. Frequently, in radio transmitting stations, 2 voltage transformations are made between the supply feeder and the rectifier. In situations of this character the most effective location for the filter appears to be between the 2 transformer banks. In special cases the most practicable filter design may be found to consist of shunt capacitors only, and in one case on which estimates have been made the most effective location for the shunt capacitors appeared to be on the rectifier side of the rectifier transformer. In a majority of the cases examined, however, the best location for the shunt capacitors has been found to be immediately adjacent (on the line side) to the rectifier transformer, or, if a regulator is used, on the line side of the regulator.

Table II—Effectiveness of Filter in Rectifier Supply Circuit

Frequency Cycles Per Second	Feed No. 1 Line Voltage (%) Filter Out	Filter In	Feed No. 2 Line Voltage (%) Filter Out	Filter In
300	4.0	2.55	6.62	3.40
420	3.51	0.80	5.35	1.42
660	2.07	0.30	2.70	0.35
780	1.55	0.15	2.01	0.21
1020	1.08	0.076	1.88	0.084
1140	1.10	0.047	1.84	0.066
1380	0.93	0.031	1.49	0.12
1500	0.85	0.034	1.44	0.047
T.I.F	220.	29.5	380.	37.5

The effectiveness of the filter mentioned in the preceding paragraph, consisting of 15-μf capacitors Δ-connected and series reactors of 13 mh, is illustrated in Table II. In a filter of this type the series reactors must be designed to carry continuously the full fundamental frequency phase current required by the rectifier and to withstand safely momentary current-surges resulting from short circuits in the rectifier station. The capacitors must be designed to withstand the peak voltage to which they may be subjected, including both the fundamental frequency voltage and the arithmetic sum of the harmonic voltages. The effect of the filter on voltage regulation must be taken into account.

In designing a filter of this type it is necessary to consider the possibility of various conditions of resonance between the filter and the system which might adversely affect the effectiveness of the filter.

In certain cases in which it is desired to reduce only a small number of harmonic components in the circuit supplying a rectifier, resonant shunts tuned to the frequencies of these components might be substituted for the shunt capacitors shown in Fig. 11. In computing the effectiveness of such an arrangement at a given frequency the effective resistance of the resonant shunt tuned to that frequency should be substituted for Z_{Cpn} in eq 35. Since this effective resistance, r_{pn}, would be small and at right angles to Z_{Lsn} and Z_{sn}, eq 35 in this case would reduce to approximately:

$$I'_n = \frac{V_{\phi-N}}{3n} \cdot \frac{r_{pn}}{Z_{Lsn} + Z_{sn}} \cdot \frac{1}{\sqrt{R_0^2 + Z_{tn}^2}} \qquad (37)$$

In some cases the series reactors may be omitted and eq 37 may be reduced still further by eliminating Z_{Lm}.

At frequencies other than those for which shunts are provided, the effectiveness can be computed from eq 35 by substituting for Z_{Cpn} the impedances of all the resonant shunts in parallel at the frequency in question. At these frequencies there is a possibility of adverse resonance conditions involving the resonant shunts and other portions of the system and in each case this possibility must be investigated.

In computing the effectiveness of a filter of this type it should be noted that all impedances are taken as phase-to-neutral impedances. Where equal shunt elements are Δ-connected, therefore, their impedances should be divided by 3 when used in the formulas.

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Petersen Coil Tests on 140-Kv System

Petersen coils installed on part of a 140-kv transmission system operating with the neutral ungrounded have successfully eliminated a large percentage of interruptions due to line-to-ground faults which occurred on that section. Detailed tests, presented in this paper, also have been made, and indicate many characteristics of the Petersen coil system.

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THE 140-kv transmission system of the Consumers Power Company in the state of Michigan has a total connected length of approximately 1,000 miles and is operated with the neutral ungrounded; protection is provided by means of directional phase and directional ground relays, the latter operating on residual charging current and residual voltage to ground.[1] A study indicated that the installation of ground fault compensating coils offered possibilities of improving system operation by permitting line-to-ground faults to be cleared without circuit interruptions.

In order to determine the efficacy of such coils on the 140-kv transmission system, initial installations of Petersen coils were made in 1931 on a portion of this system which was isolated from the remainder by delta-delta connected transformers. These Petersen coils, each rated at 10,773 kva, were installed at the Saginaw River plant and at the Alcona hydroelectric plant. During August 1931, the Consumers Power Company with the assistance of the Joint Subcommittee on Development and Research of the Edison Electric Institute and the Bell Telephone System, and the General Electric Company, conducted extensive field tests to study the operation of the coils under a wide range of conditions. These included various fault conditions with the Petersen coils in service, with the neutral isolated, and with the neutral grounded by means of a grounding bank.

The following conclusions may be drawn from the results of these tests and subsequent operating experience:

1. The shock to the system during line-to-ground faults is very small with the Petersen coils in service and the ground fault current is of a low value.

2. The tuning of the Petersen coils may be determined either by calculations, by ammeter tuning, or by fault tuning. The operation of the coils when in tune is not affected by the location of the fault or by the particular conductor faulted.

3. Successful operation of the coils as regards arc extinction requires that the uncompensated fault current be kept to a low value. In this connection it is very important that the line conductor sizes and the transmission voltage be properly correlated so that the corona current will not be excessive during fault conditions.

4. The maximum overvoltages recorded during the tests were approximately 3 times normal and in no case were there any excessive voltages attributable to arcing grounds, Petersen coil resonance, or to any other causes.

Operating experience on the Petersen coil section of the system during the past $2^1/_2$ years has demon-

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Full text of a paper recommended for publication by the A.I.E.E. committee on protective devices, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 23–26, 1934. Manuscript submitted Oct. 30, 1933; released for publication Nov. 13, 1933. *Not published in pamphlet form.*

[1] For all numbered references see list at end of paper.

strated that the coils successfully eliminate a large percentage of interruptions due to line-to-ground faults. The use of the coils does not interfere with the normal routine operation of the system.

THEORY OF PETERSEN COIL OPERATION

A ground fault compensating coil is an inductance suitable for connection in a transmission system in such a manner that, in case of an arc from one conductor to ground, the fault current will be of such low value that the arc will be self-extinguishing under conditions usually encountered. The original form of this device, developed by Dr. Petersen in Germany and therefore termed a Petersen coil, consists of an inductance connected between ground and the neutral point of a wye-delta connected transformer bank operating on a transmission system which is otherwise ungrounded.

A simplified diagram of connections is shown in Fig. 1(*a*), in which the capacitance between ground and each of the 3-line conductors is represented by C_1, C_2, and C_3. Consider this first as an isolated neutral system (neutral switch S open) and neglect leakage resistances and circuit losses. With a fault to ground on conductor 1, the voltage across C_1 falls to zero, while the voltages across C_2 and C_3 become line-to-line voltage, E_{2G} and E_{3G}, respectively, as shown by the vector diagram of Fig. 1(*b*). The current in the fault $(I_{2G} + I_{3G})$ will then be the sum of the currents through the capacitances to ground. This current will lead the residual voltage E_R by approximately 90 deg, as shown in Fig. 1(*b*). Consider now that the Petersen coil, a variable inductance, is connected between neutral and ground (switch S closed). The voltage between neutral and ground E_{GN} $(E_R/3)$ impressed across this inductance will cause a current I_{NG} $(-I_P)$ to flow which will lag this voltage by approximately 90 deg. As the path of this lagging current is also through the fault, the fault current will now become the vectorial sum of $-I_P$ and $+I_C$. If the Petersen coil is tuned so that its inductance is of the correct value, I_P will be equal and opposite to I_C and, neglecting losses, the fault current will theoretically be zero. Actually, losses due to conductor resistance, corona, etc., cause a small amount of in-phase current (not shown in this vector diagram) which is not balanced out by the Petersen coil. This unbalanced current in the fault is expected to be of such a small value that arcs over insulator strings, or across gaps of the same lengths, will be unstable and will be broken by air currents within a few cycles.

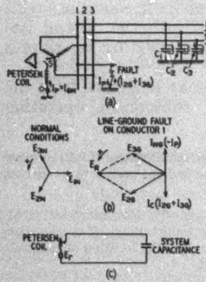


Fig. 1. Petersen coil system, showing (a) system connections, (b) simplified vector diagram, and (c) equivalent single phase circuit

E_{1G}, E_{2G}, E_{3G} = line-to-ground voltages
E_R = residual voltage to ground $= E_{1G} + E_{2G} + E_{3G}$
I_C = charging current to ground from sound phases
I_P = Petersen coil current, ground to neutral

Since under normal operating conditions voltage between neutral and ground is of very low value, the Petersen coil can be left in the circuit at all times and hence is at once effective in case of a fault to ground. Provision is sometimes made for taking the coil out of service in case a permanent fault develops (such as, a conductor on the ground, a punctured insulator, etc.). Obviously, the Petersen coil can be effective in clearing trouble only when the fault is an arc from one conductor only to ground inasmuch as trouble involving more than one conductor constitutes a line-to-line short circuit.

PREVIOUS OPERATING EXPERIENCE

Although the installation of Petersen coils on the Consumers Power Company system is the first application to systems above 100 kv in this country, it is not to be inferred that they are a new development in the art. The first coils were built and installed in Germany in 1917, and since then the installation of ground-fault compensating coils has come to be considered standard practice in Germany (the law there prohibits solidly grounding the neutral), with the result that today practically all high voltage systems there are so equipped. Lines protected by these coils total 100,000 miles in length with operating voltages as high as 220 kv.

In 1921 the first Petersen coil in the United States was put in service on a 93-mile 44-kv system in Alabama.[2,3] The coil used in this installation was later found to have certain electrical characteristics which permitted resonant conditions and consequent overvoltages. (To eliminate this behavior, coils are now designed to saturate at abnormal voltages and so destroy the condition of resonance with rise of voltage.) Its service record, however, was satisfactory as it neutralized approximately 55 per cent of the faults which occurred on the system. The coil was taken out of service when extensive changes were made on the 44-kv system, which resulted in a considerable increase in the connected circuit mileage. The coil was moved to a location on the Georgia Power Company's system where it has been in successful operation on a small 44-kv section of line up to the present time.

DESCRIPTION OF INSTALLATIONS

The 140-kv lines of the Consumers Power Company having a total connected length of approximately 1,000 miles are arranged in the shape of a large "U" extending along the eastern and western sides and through the southern portion of the state of Michigan. Power is generated by hydroelectric generating stations and by steam generating stations located at various advantageous points close to the load centers. The system is interconnected with the Detroit Edison Company through a 132-kv transmission line and a 30,000-kva transformer bank.

The 2 Petersen coils installed on the system of the Consumers Power Company in 1931, one at Saginaw and one at Alcona, were manufactured by the General Electric Company and have identical characteristics. They are each rated: 10,773 kva, 133 amp, 60 cycles, 81 kv, and are protected by a thyrite resistor installed inside the tank under oil and connected across the terminals. Tap changing under load equipment is provided which permits the use of any of the taps indicated in Table I.

Table I—Petersen Coil Characteristics

Tap	Impedance	10-Min Rating
1	4.46 + *j*1482 ohms, 100.0%	56.6 amp
2	3.95 + *j*1206 ohms, 81.4%	86.4 amp
3	3.55 + *j*1020 ohms, 68.8%	75.7 amp
4	3.17 + *j*870 ohms, 58.8%	86.2 amp
5	2.97 + *j*770 ohms, 52.0%	95.2 amp
6	2.76 + *j*676 ohms, 45.7%	105.0 amp
7	2.60 + *j*611 ohms, 41.3%	115.0 amp
8	2.46 + *j*556 ohms, 37.5%	125.0 amp
9	2.38 + *j*515 ohms, 34.8%	133.0 amp

At Saginaw the coil is connected in the neutral of a 9,000-kva wye-delta connected transformer bank having a zero sequence impedance of 76 + *j*638 ohms. At Alcona the main 9,000-kva station transformer bank is connected wye-delta with the Petersen coil in the neutral circuit. The zero sequence impedance of this transformer bank is 17 + *j*202 ohms. Each coil was specified to cover a range of 75 to 175 miles and to have taps which would be suitable for tuning equal increments of line, which required that the percentage change in impedance between the Petersen coil taps be smaller at the higher taps.

The installations are arranged so that if a line-to-ground fault persists, the Saginaw coil will be short-circuited by an oil circuit breaker controlled by a definite time overcurrent relay and the neutral circuit at the Alcona plant will be opened by a circuit breaker after a similar time delay. The neutral of the system then will be grounded directly by the Saginaw bank permitting ordinary directional residual ground relays to clear the section of line in trouble.

PURPOSE OF TESTS

The purpose of the tests was to determine experimentally the proper tuning for the coils as compared with calculated tuning points and to check the operation of the coils under various fault conditions similar to those which might be expected in practice. Tests were made to determine the tuning point as indicated by observation of the neutral current under normal conditions, and compare it with the tuning point determined by measurements of fault current under fault conditions. Observations were made regarding the effect on coil tuning of the location of the fault, the conductor faulted, and the operation of the system at voltages ranging from 70 to 140 kv. A study was made of the performance of the system with Petersen coils as compared with its behavior as an isolated neutral or grounded neutral system.

The tests may be divided into the following classifications:

1. Tuning of Petersen coils with power system
   - *a.* Method using neutral ammeter under normal conditions
   - *b.* Method involving line-to-ground faults
2. Line-to-ground fault tests with neutrals of wye-delta transformer banks at Saginaw and Alcona connected:
   - *a.* Isolated
   - *b.* To ground through Petersen coils
   - *c.* Directly to ground (high impedance grounding bank)
   - *d.* To ground through resistance
3. Harmonic analysis of power system wave shape with the neutrals of the wye-delta transformer banks at Saginaw and Alcona connected:
   - *a.* Isolated
   - *b.* To ground through Petersen coils
   - *c.* Directly to ground (high impedance grounding bank)

Tests were made with the transmission lines operating at voltages from 70 to 140 kv with various Petersen coil taps, different values of neutral impedance, etc.

ELECTRICAL CHARACTERISTICS OF TEST SYSTEMS

The electrical characteristics of that portion of the system set apart as the Petersen coil system are shown in Fig. 2. It will be noted that this is a 226-mile portion of the 140-kv network isolated from the remainder of the system through delta-delta transformer banks. During the staged tests this section was taken out of service and energized from

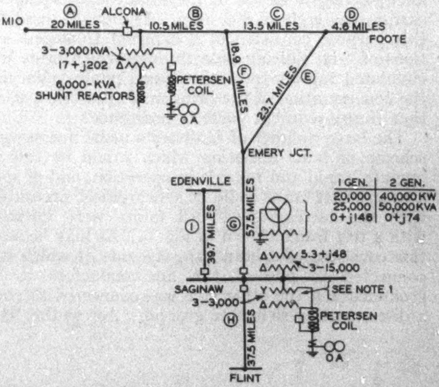


Fig. 2. Electrical characteristics of the test system

Line Section	R + *j*X₁ Ohms	Z₁ Ohms	Conductor Size	Conductor Spacing
A	10.6 + *j*17.5	20.5	110,000 cir mils	15.4 ft
B	5.59 + *j* 9.19	10.8	110,000 cir mils	15.4 ft
C	7.19 + *j*11.8	13.9	110,000 cir mils	15.4 ft
D	2.45 + *j* 4.02	4.71	110,000 cir mils	15.4 ft
E	12.6 + *j*20.8	24.4	110,000 cir mils	15.4 ft
F	10.1 + *j*16.5	19.3	110,000 cir mils	15.1 ft
G	30.6 + *j*50.3	58.9	110,000 cir mils	15.4 ft
H	19.1 + *j*32.6	37.9	110,000 cir mils	15.4 ft
I	17.5 + *j*34.2	38.4	No. 2/0	15.1 ft

Note 1. Transformer impedance equals 76 + j638 with high voltage windings connected in series; and 30 + j159 with high voltage windings connected in parallel
Measured line capacitance equals 0.0087 μf per mile
Ohms impedance given on 140-kv base

an independent power source located at Saginaw and consisting of either 1 or 2 20,000-kw turbine-generators. The majority of the transmission line conductors on this 226-mile portion consisted of 110,000 cir-mil copper. All circuits except the Saginaw-Edenville line are of single circuit construction arranged in triangular configuration without ground wires.

TEST EQUIPMENT SET-UP

As it was desired to make measurements at a number of points on the system, the set-up of recording equipment was necessarily quite complicated. Because quantities to be measured were likely to vary rapidly with time, and as fault conditions were to be of very short duration, practically all records were made by means of oscillographs operating at reasonably high film speed, supplemented in a few cases by recording ammeters.

At Alcona no potential transformers were available for the measurement of 140-kv line-to-ground potentials. Use was therefore made of 50-ft water hose potentiometers similar to those previously used with entire satisfaction on similar test work.[4] At all other locations measurements were made through conventional current and potential transformers.

The test schedule required the use of a neutral grounding resistor and a fault resistor to be used in simulating a fault to a tower of high footing resistance or other condition in which considerable resistance was present in the fault-current circuit. These requirements necessitated the use of a resistance varying from 100 to 1,000 ohms and capable of carrying as high as 300 amp. The device used for this purpose consisted of 2 inverted U-shaped sections of 4-in. sluicing hose through which brine was circulated rapidly by a centrifugal pump. Varying the concentration of the brine made possible a selection of any required value of resistance.

The large number of fault tests made necessary a scheme of fault initiation which would be safe to operate, rapid and reliable in operation, and of such a nature that faults could be synchronized accurately with the oscillographs. All faults were initiated with a test frame shown in Fig. 3. As may be seen, this consisted of a horn gap, one side of which was connected to one of the line conductors to be grounded and the other side was connected through a disconnecting switch to ground. Across this horn gap was placed a 2-amp fuse wire when arcing faults were required, and a copper jumper when a solid fault was required. With the disconnecting switch open, the system was free of grounds and operated normally. At a given signal, rung over telephone lines, all oscillographs were started and at the test frame, a trap was sprung, permitting a weight to fall. This weight was attached to the disconnecting switch through a slack rope and after about 0.5-sec time delay, tightened up the rope and snapped the disconnecting switch shut very quickly, grounding the line. Because of its high speed of closing, the disconnecting switch was undamaged by several hundred operations in which fault current was as high as 400 amp.

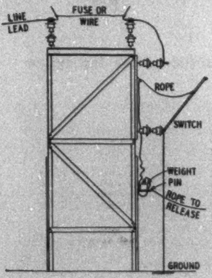


Fig. 3. Test rack

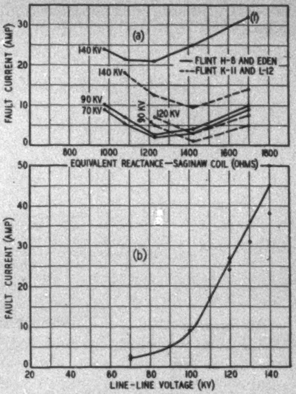


Fig. 4. Fault currents, showing (a) fault tuning tests and (b) fault current with Petersen coils in tune

PETERSEN COIL TESTS

The reactance tap at which the Petersen coils tune with the system capacitance was determined by calculations and by tests under both normal conditions and fault conditions. Ammeter tuning tests, fault tuning tests, and tests to determine the effect of corona are described in the following sections.

AMMETER TUNING TESTS

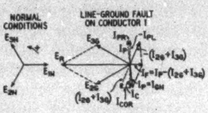
In Fig. 1(a) is represented a simple transmission system with its neutral grounded at one point through an inductance, and in Fig. 1(c) is shown the equivalent single-phase circuit to ground of this same system. In any polyphase system there is always some residual voltage to ground due to dissymmetry between phases and to ground. The voltage E_r in Fig. 1(c) represents this unbalanced voltage and with perfect tuning the current in the series circuit due to this voltage would be a maximum. In other words, when the inductance of the Petersen coil plus that of the grounding bank is tuned with the system capacitance to ground, the current in the neutral circuit will be a maximum and will be limited only by the resistive losses in the circuit.[5]

These facts were used in the ammeter method to determine the tuned tap with the system in normal conditions by noting the magnitude of the neutral current when the coil was operated on various tap positions. With the Saginaw coil connected to the Flint-Edenville lines (sections *H* and *I* in Fig. 2) the tuning was relatively sharp at tap 3 with a neutral current of 4.6 amp. The neutral current was much steadier when the test system was synchronized with the remainder of the system than when it was operated isolated, possibly due to somewhat closer control of frequency. With the Alcona coil connected to the lines north of Saginaw (sections *A* to *G*, inclusive) the tuning was broad, between taps 8 and 9, which is close to the minimum value of coil reactance obtainable. With the Mio section of line off, the tuning point was tap 6 with a neutral current of approximately 7 amp.

Fault Tuning Tests

Fault tuning tests were made by placing a solid fault-to-ground on one of the conductors with the Petersen coils on one tap position and measuring the current in the fault. The fault was then cleared manually, the Petersen coils set on a different tap and the test repeated. The coils were considered to be "in tune" when the fault current was a minimum. Curve 1 of Fig. 4(*a*) shows the results of tuning tests made at 140 kv with the Saginaw coil connected to the Flint *H*-8 and the Edenville lines. In this curve the variation of fault current is shown as a function of the equivalent neutral reactance. This equivalent neutral reactance is equal to the reactance of the Petersen coil plus one-third of the transformer reactance and is thus equal to one-third of the zero sequence reactance. This curve shows the Saginaw coil to be in tune at 1,230 ohms (tap 3) with a fault current of 21 amp. The Alcona coil, with the Au Sable section of line, tuned at 623 ohms (tap 8) with a fault current of 31 amp at 140 kv. The entire 226-mile test section was in tune with the Alcona coil on tap 8 and the Saginaw coil on tap 4. Under these conditions the fault current varied from 40 to 50 amp during different tests.

Fig. 5. Petersen coil system, showing complete vector relations at point of fault



E_{NG} = neutral-to-ground voltage
E_{1G}, E_{2G}, E_{3G} = line-to-ground voltages at fault ($E_{1G} = 0$)
E_R = residual voltage to ground = $E_{1G} + E_{2G} + E_{3G}$
I_C = charging current to ground from sound phases 2 and 3
I_{COR} = equivalent leakage current to ground due to corona
$I_{2G} + I_{3G}$ = resultant line-to-ground current from phases 2 and 3
I_{PL} = inductive component of Petersen coil current
I_{PR} = resistive component of Petersen coil current
I_P = Petersen coil current, ground to neutral
I_F = fault current

Tests were also made to determine the effect of different fault locations on the coil tuning. It was found that a change in fault location caused no definite change in tuning with operating voltages ranging from 70 to 140 kv. The tuning of the coil was the same regardless of which conductor was faulted. It also was found that the results were practically the same irrespective of whether or not the test system was synchronized with the remainder of the system through delta-delta transformer banks at Saginaw. However, with the system synchronized, the fault current contained a number of harmonics, particularly the third, fifth, and seventh.

Effect of Corona

It may be seen from the above that although the changing of the coil taps caused a change in the magnitude of the fault current, the minimum value of fault current obtainable on the 226-mile system was surprisingly high in value. In order to determine the cause of this high current, tests were made at various operating voltages ranging from 70 to 140 kv line-to-line. In Fig. 4(*b*) is shown the minimum values of fault current obtained with the entire test system operating at these voltages and with the coils operating on the tuned taps. This curve shows that the fault current was not directly proportional to the voltage, but rather varied as some higher power of the voltage and suggests that the difficulties encountered may be due to corona. The tuning curves for different coil operating taps were of the same general shape as those shown in Fig. 4(*a*). The wave shape of the fault current was in general more irregular for faults at 140 kv than at 70 kv, probably due to the presence of harmonics caused by corona at the higher voltages. The equivalent coil reactance required for the tuning at 140 kv was 415 ohms as compared to 455 ohms at 70 kv, indicating that the system capacitance to ground was greater at the higher voltage. The results of these tests are further illustrated by Table II.

Table II—Summary of Fault Tuning Tests, Saginaw and Alcona Coils

Sag. Bus Voltage	Tuned Taps	Fault Current (I_f)	Remarks
140 kv	*S*3, *A*8	38–50 amp	Tuning curve flat
130 kv	*S*3, *A*8	31–36 amp	Tuning curve flat
120 kv	*S*3, *A*8	24–27 amp	
70 kv	*S*1, *A*8	Approx. 2 amp	Tuning curve sharper than at 140 kv

The critical corona voltage on a 110,000-cir-mil 3-phase line is of the order of 125 kv rms line-to-line with the system operating normal, and about 100 kv with one conductor grounded. A considerable amount of corona might therefore be expected under line-to-ground fault conditions at 140 kv and would be evidenced as fault current since the in-phase component of corona current to ground adds directly to the resistive losses in the circuit. That this uncompensated current is produced by some form of system loss is further substantiated by the fact that the fault current to ground ($-I_f$) was found to be practically in phase with the residual voltage as illustrated by Fig. 5. As a further check on this possibility, tests at various voltages were made, using the Saginaw-Flint *K*-11 and *L*-12 lines in place of the Flint *H*-8 and Edenville lines with the Saginaw coil. The *K*-11 and *L*-12 lines comprise a twin circuit line of No. 000 copper conductors with one ground wire and have a total circuit length of 87.6 miles. These lines, with their larger conductors, consequently have less corona loss than the Flint *H*-8 and Edenville lines. The curves of Fig. 4(*a*) show the variations of fault current with tap setting and voltage as determined by graphic ammeter records and checked by oscillograms. It may be seen that the effect of a change in wire size was much more pronounced at 140 kv than at the lower voltages. The *K*-11 and L-12 lines have a slightly greater total circuit length than the other pair of lines, but the expected increase in capacitance due to this was apparently more than offset by the decrease in capacitance resulting from the *K*-11 and *L*-12 lines being on the same towers. The *K*-11 and *L*-12 lines tuned on tap 2 with a much lower value of fault current, particularly at the higher voltages than the Flint *H*-8 and Edenville lines. The effect of varying voltage or wire size, the phase relation between fault current and residual voltage and calculations of critical corona voltage all indicated that the high values of fault current were the result of excessive corona loss under fault conditions.

TESTS WITH SYSTEM NEUTRAL ISOLATED, OR GROUNDED

A number of single-line-to-ground fault studies were made on the test system with the neutral isolated or grounded by means of a grounding bank, directly or through resistance. Part of these tests were made to compare the performance with that observed with the Petersen coils in operation; some were made to study other problems, taking advantage of the conveniences of the Petersen coil test set-up. The transformer bank used in the "grounding bank" tests had a relatively high impedance (76 + *j*638 ohms) and this test condition therefore cannot be termed solidly grounded even though the neutral of the bank was directly grounded. In all these tests, conditions were somewhat abnormal in that the amount of generating capacity and transformer capacity as compared to the length of the test system was only approximately one-half normal, and at the instant of fault the generators were operating at practically no load and with very low values of excitation. Table III shows a comparison of the performance of this system with the various forms of neutral connections. The simplified system connections and the vector relations for the isolated and grounded neutral conditions are illustrated by Fig. 6 and Fig. 7, respectively.

During the isolated neutral tests at 140 kv the fault currents ranged from 355 to 455 amp with zero ohm faults. These currents were considerably higher in magnitude than had been indicated by preliminary calculations, which neglected corona currents. Moreover, in the isolated neutral tests, abnormal generator conditions (described above) became particularly important because of the large amount of charging current to ground which appeared as a capacitive load on the generators, tending to increase the excitation during faults. While this was somewhat counteracted by the eventual reduction in speed due to the large unbalanced load, the generator voltage rose considerably during the early period of faults. It therefore may be concluded that the increase in fault current over what might normally be expected was evidently due largely to corona on the unfaulted conductors and to the increased charging current to ground, both of which were materially affected by the high voltage between the unfaulted conductors and ground.

The grounding tests were made with the neutral of the 9,000-kva wye-delta transformer bank at Saginaw grounded either solidly or through resistance ranging from 100 to approximately 1,000 ohms. This bank was originally designed for 30-cycle operation and its impedance was therefore relatively high at 60 cycles. The bank when solidly grounded tended to act similarly to a Petersen coil approximately 50 per cent out of tune. During the neutral resistance tests the bank was connected first with the high voltage windings in series ($Z = 76 + j638$) and then in parallel ($Z = 30 + j159$). It was rather striking to note that the residual voltage and fault current increased while the neutral current decreased with increasing neutral resistance, contrary to what might at first be surmised. These results were due to the effect of the transmission line capacitance to ground on the total circuit impedance. The zero sequence capacitive impedance of the test system acted in parallel with the equivalent impedance of the grounding bank and neutral resistance in limiting the fault current, and with neutral resistances above approximately 160 ohms the system capacitance became controlling. The

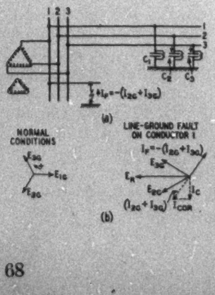


Fig. 6. Isolated neutral system showing (a) system connections, and (b) vector relations

Symbols same as shown for Fig. 5

Fig. 7. Grounded neutral system showing (a) system connections, and (b) vector relations

Symbols same as shown for Fig. 5 except as follows:
I_N = current in neutral = I_{GN}
I_C = charging current to ground from sound phases 2 and 3 assuming corona current negligible·

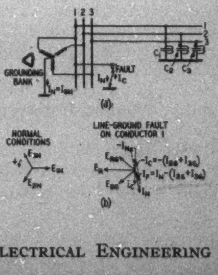


Table III—Comparative Typical Values of Currents and Voltages for Solid Low Resistance Faults at 140 Kv

Equiv. Neut. Impedance[1] (Ohms)	Neutral Resistance (Ohms)	Fault Current (Amp)	Current in Neutral (Amp)		Saginaw Residual Voltage (Kv)	Maximum Line-Ground Voltage (Times Normal[2])	Shock to Power System
			Saginaw	Alcona			
Petersen coil tests							Slight
	0	40–50	30–60	130–180	250–290	2.0 (2.7)	
Isolated neutral tests							Severe
		350–450			390–410	2.9 (3.5)	
Grounding bank							Severe
25 + *j*213	0	110–120	180–200		130–140	1.4 (2.0)	
Neutral resistance (high voltage windings in series)							Severe
160 + *j*213	135	140–150				1.6	
375 + *j*213	350	170–180				1.9	
545 + *j*213	520	230				2.1	
Neutral resistance (high voltage windings in parallel, power suplied by 2 generators)							Severe
110 + *j*53	100	290	250		240	1.3	
380 + *j*53	370	270	160		200	1.9	
830 + *j*53	820	320	110		290	2.3	
1010 + *j*53	1000	310	100		310	2.4	

1. Value of neutral impedance given includes impedance of grounding bank and is expressed as one-third of the "per phase" value.
2. Times normal is equal to the maximum observed crest value divided by the normal crest value prior to the fault. Some of the maximum voltages listed were obtained during arcing faults.

Values in parentheses are based on surge recorder records, others on oscillograms.

Table IV—Relative Magnitudes of Induced Voltages

Neutral isolated	1.0
Petersen coils	0.4
High impedance grounding bank	0.7
Neutral resistance	1.4

resultant zero sequence impedance then had a capacitive reactance component which was neutralized to some extent by the inductive reactances of the positive and negative sequence impedances.

One of the most interesting features of the comparative tests was the observation of shock to the generators at the time of faults. With the Petersen coils in service there is practically no discernible effect. The severity of the shock was greatest when the neutral was isolated and somewhat less when the neutral of the grounding bank was grounded through a resistance.

BEHAVIOR OF ARCS

It may be observed from Table III that with the Petersen coils in service the fault current was very much less than with the system neutral isolated or grounded. Obviously, an arcing fault on this Petersen coil system, because of its lower current, would be much less damaging to insulators, line conductors, and hardware, than would a similar fault on the other types of systems. A few tests were made with the system neutral isolated, grounded or connected to the Petersen coils to study experimentally the effect of circuit characteristics on the tendency of the arc to be self-extinguishing. Although the number of tests was too limited for definite conclusions, the tendency seemed to be for arcs of low current value to be less stable than those of higher value.

INDUCTIVE INFLUENCE TESTS

The toll circuits of the Michigan Bell Telephone Company parallel the Saginaw-Emery Junction-Foote 140-kv transmission lines north of Saginaw for considerable distances at various separations, ranging from 65 ft to approximately 3 miles. Harmonic analyses and measurements of induced voltages and noise were made on the toll circuits in conjunction with the tests on the power system. The relative magnitudes of the low frequency voltages induced during the different power system operating conditions are given in Table IV for faults at Alcona. These relative values of induced voltages would be altered, of course, for other situations according to the separation between the circuits, fault location, etc. For convenience in comparing the values, the induced potential with the system neutral isolated has been used as a reference.

The higher induced voltage for the neutral resistance condition is explained by the increased fault current over that for the grounding bank condition. This increase is due to the capacitive nature of the zero sequence impedance which is comparable in magnitude with other reactive impedances of the circuit.

The results of the harmonic analyses showed that under normal operating conditions the harmonic content of voltages to ground, residual to ground and neutral current of the power system, was practically the same for the various neutral connections. The most prominent frequencies observed were 180, 300, and 420 cycles. The noise observed on the telephone circuits was about equal for the various neutral connections.

OVERVOLTAGE CONDITIONS

As a part of this investigation a study was made of the voltages produced on the line conductors by various types of faults under different system conditions. Table V shows the maximum voltage between conductor and ground recorded by the oscillographs at the time of faults of the type indicated. As may be noted voltages on the isolated neutral system were the highest of the group, voltages on the Petersen coil system next, and those of the resistance or solidly grounded system were lowest.

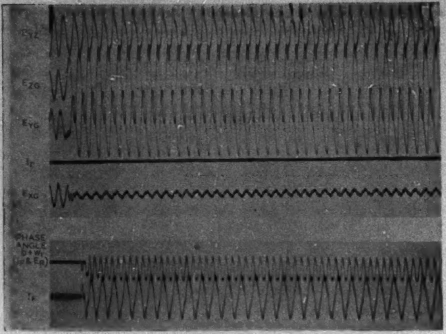


Fig. 8. Oscillogram of solid fault to ground with isolated neutral system

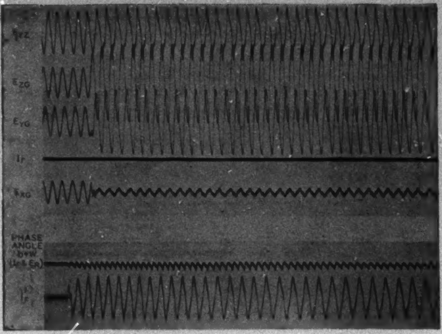


Fig. 9. Oscillogram of arcing fault with isolated neutral system

Table V—Conductor to Ground Voltages (Times Normal)

	Oscillographic Record		Surge Recorder Record	
Type of System	Solid Fault	Arcing Fault	Solid Fault	Arcing Fault
Petersen coil	2.0	2.0	2.7	2.2
Isolated neutral	2.9	2.8	3.2	3.5
Grounding bank	1.4	No tests	2.0	No tests
Neutral resistance	2.4	2.3	2.5	2.5

It is of interest to note that voltages resulting from arcing faults are of the same magnitude as those resulting from solid faults and that in no case did they exceed 3.5 times normal (2.9 times normal by oscillograms). In all the tests made, either with solid or arcing faults, the voltage between sound conductors and ground was predominately 60 cycles, sometimes with some third or fifth harmonics superposed. (See Figs. 8 and 9.) In no case was there evidence of cumulative overvoltages due to restriking of the arc. These data, with other information previously presented,[4] seem to discredit the many theories based upon arc extinction which have been proposed regarding arcing ground faults and which, on isolated neutral systems, predicted overvoltages of as high as 7 times normal. All these theories have required that the arc break and restrike at certain parts of the cycle, resulting in an accumulation of voltage which according to certain theories had high frequency characteristics.

Clearing of Permanent Ground Faults

Petersen coils can, of course, be effective as regards the extinction of arcs only in case of faults which are of a momentary nature, such as flashovers. Other faults, such as exist when conductors lie in contact with ground, are of a permanent nature and cannot be cleared by Petersen coil operation. In such cases the line involved must be deënergized by circuit breaker operation, either manually or automatically by protective relays. Directional ground relays, such as are commonly used for transmission line protection, depend for their operation upon the magnitude and phase relations of the currents and voltages existing during fault conditions. A study of these quantities as determined during the staged tests indicates that with permanent faults it would be very difficult, if not impossible, to obtain proper relay selectivity with the Petersen coils in service. The most feasible means of clearing such faults when they have developed appears to be to short out the coil by a suitable relay, thus effectively grounding the system, and then to select the faulted circuit by the use of ordinary ground relays. Numerous complications are involved in the application of such a relaying scheme to a network where several coils are installed at widely separated localities. Studies have indicated that practicable solutions to this problem may be effected by one or more methods.

Petersen Coil System Operating Record

Following the staged tests, the Petersen coils were put into regular operation on the system on August 27, 1931, and remained in service until October 17, 1931, when their operation was discontinued because no more serious lightning storms were anticipated that year. The coils were again put in service on February 13, 1932, and have been in continuous service during the remainder of 1932 and all of 1933. In 1933, one more line between Saginaw River Steam Plant and Flint was added to the Petersen coil system, increasing the total length of lines connected to 276 circuit miles. During the entire time the coils have been in operation, their performance has been recorded by a 6-element automatic oscillograph and 2 high-speed curve-drawing ammeters. The ammeters, one located at Saginaw and one at Alcona, record the current through the respective coils. The automatic oscillograph, located at Saginaw, records the voltages of the *X*, *Y*, and *Z* conductors with respect to ground, residual voltage, Petersen coil current, and residual current in the *H*-8 line north of Saginaw. From these instruments it has been possible to get a very complete story of the nature of the faults, their duration, the nature of the transient at the time the fault is cleared, and other important information.

Table VI gives a summary of the performance of the Petersen coil system for its entire period of operation up to the end of August, 1933. As may be seen, practically every single-line-to-ground fault has been eliminated without circuit breaker operation and subsequent outages to the lines. As line to line faults are unaffected by the Petersen coils, faults of this nature in most cases required breaker operation for their elimination.

The length of time required for ground faults to clear themselves is shown by Fig. 10. From this curve it may be seen that 50 per cent of all ground faults cleared in less than 20 cycles and 70 per cent cleared in less than 60 cycles. The maximum length of time required for a fault to clear was 14 sec. The location of this 14-sec fault was definitely determined and the damage to insulators and line hardware found to be insignificant, indicating that arcs constituting ground faults on this Petersen coil system are not very damaging in effect. Up to date (August 31, 1933), only one record has been obtained indicating that a fault which started as a ground fault developed into a short circuit before being cleared. As indicated in Fig. 10 a large number of ground faults have been entirely eliminated in less than 5 cycles. That the rapid elimination of the faults is a characteristic of the Petersen coil system is evidenced by the fact that automatic oscillographic records taken on the balance of the Consumers Power Company's 140-kv system operating with isolated neutral (length approximately 600 miles, ground fault current approximately 900 amp) show no faults clearing in less than the time required for relaying and breaker operation. The limited value of fault current on the Petersen coil system possibly prevents the establishment of even a semi-stable arc in a large percentage of the cases.

An oscillographic record of a typical ground fault is shown in Fig. 11. It may be noted that during the period of this fault, the voltage waves were very little distorted from sine waves with the exception of that on the faulted conductor, which was the voltage of the arc. At the start of the fault, the sound conductor voltages rose to line-to-line voltage with no evidence of excessive magnitudes due to arcing grounds. (The maximum voltage recorded by the oscillograph since the coils went into operation is 2.8 times normal.) As the arc was increased in length by the wind, the faulted conductor voltage rose gradually while the sound conductor voltages decreased accordingly. When the arc was extinguished, all voltages returned to normal within a few cycles without any unusual behavior. On a few oscillograms, restriking of the arc has been indicated. Faulted conductor voltage rose to almost normal value, apparently as the arc was increased in length by the wind and voltage values approached normal. Then as the arc restruck, and its length substantially decreased, voltage conditions again became characteristic of line to

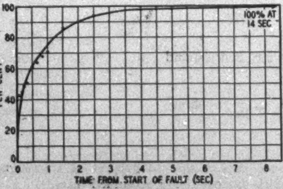


Fig. 10. Percentage of ground faults self-cleared in various lengths of time. Total number of faults 52

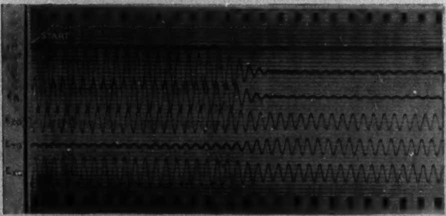


Fig. 11. Oscillogram of typical ground fault

I_r = residual current in Saginaw-Emery Junction line
I_P = Petersen coil current
E_R = residual voltage to ground
E_{XG}, E_{YG}, E_{ZG} = line-to-ground voltage

Table VI—Summary of Petersen Coil Operation

	1931, Aug. 27– Oct. 17	1932, Feb. 13– Dec. 31	1933, Jan. 1– Aug. 31	Total
Cause of Faults				
Lightning	12	27	46	85
Sleet	0	3	0	3
Unknown and other causes	1	2	10	13
Total	13	32	56	101
Type of Fault and Method of Clearing				
Line to ground faults	6	16	31	53
Self-clearing, no line interruption	5	16	30	51
Cleared by breaker operation	1[1]	0	1[2]	2
Short circuits	1	9	6	16
Self-clearing, no line interruption	0	1	0	1
Cleared by breaker operation	1	8	6	15
Faults which could not be definitely classified as to nature[3]	6	7	19	32
Self-clearing, no line interruption	4	4	15	23
Cleared by breaker operation	2	3	4	9
Per cent of all faults cleared without interruption to line	69	66	80	74

1. Line failure, insulator string parted
2. Developed into a short-circuit
3. Includes faults which because of lack of oscillograms or difficulty of interpretation could not be definitely classified as short circuits or ground faults

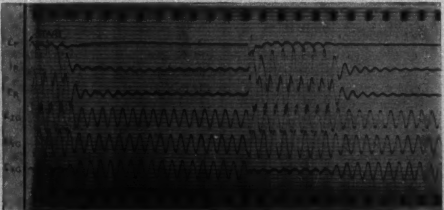


Fig. 12. Oscillogram of recurring fault

Symbols same as shown for Fig. 11

ground faults. The transition between these 2 conditions occurred without abnormal voltage on any of the conductors, although irregular waves of moderate value were recorded in the record of Petersen coil current and residual current.

A type of fault which has been recorded in a few cases is shown in Fig. 12. This oscillogram indicates that a ground fault on the X conductor was cleared in less than 5 cycles. Normal conditions were established on the system, but at the end of 17 cycles the fault recurred on the X conductor and was again cleared after 9-cycles duration. Faults of this type have a similarity in that the second disturbance began within 30 cycles of the start of the first and affected the same conductor, with no evidence of overvoltage being recorded by the oscillograph. It has been suggested that these repeating faults have been caused by multiple strokes of lightning, the first stroke establishing a fault which was quickly cleared, only to be followed by another established by a second stroke of lightning, possibly at the same tower. That multiple strokes of lightning going to earth at the same point are rather common in occurrence has been well established by pictures made with revolving cameras.[6]

CONCLUSIONS

The following conclusions may be drawn from the results of the staged tests and the subsequent operating experience:

1. The shock to the system during line to ground faults is very small with the Petersen coils in service, being considerably less than with the neutral either isolated or grounded through a high impedance grounding bank.
2. The ground fault current with the Petersen coils in service is relatively small.
3. The tuning of the Petersen coils for a given system may be determined either by calculations, by ammeter tuning, or by fault tuning. The operation of the coils when in tune was not affected by the location of the fault or by the particular conductor selected for the fault.
4. Successful operation of the coils as regards arc extinction requires that the uncompensated fault current be kept to a moderately low value, probably less than 50 amp. The magnitude of the fault current is vitally affected by the length of the connected system and the amount of leakage current to ground, including corona. It is very important that the line conductor sizes and the transmission voltage be properly correlated so that the corona current will not be excessive during fault conditions.
5. The maximum overvoltages recorded during the staged tests were approximately 3 times normal. In no case were there any excessive voltages attributable to arcing grounds, resonance between the Petersen coils and the line capacitance, or to any other causes. The voltage conditions during arcing and solid fault conditions were practically identical.
6. The clearing of permanent line to ground faults by automatic relay operation involves certain complications on a Petersen coil system, but it appears that these may be taken care of in a practical manner.
7. Operating experience on the 276-mile section of this system has demonstrated that the Petersen coils successfully eliminate a large percentage of interruptions due to line to ground faults. In 96 per cent of the cases of ground faults (74 per cent of all faults) the arc has been extinguished and the fault cleared without line interruptions.
8. Faults of the current magnitude experienced in this section (approximately 50 amp or less) require various lengths of time for extinction. Some apparently do not develop into a stable condition and are extinguished within a very few cycles, while others continue for several seconds. The local arc damage has been found to be insignificant.
9. The Petersen coils do not affect or handicap the normal routine operation of the system, except to require change of tap setting with changes in length of connected transmission lines.

Acknowledgment is made to the Joint Subcommittee on Development and Research of the Edison Electric Institute and the Bell Telephone System, to The Michigan Bell Telephone Company, and to the General Electric Company, for the extremely valuable assistance rendered by these organizations. Special recognition is due to A. C. Connell, I. R. Dohr, J. M. Dunham, A. F. Gramm and J. K. Peck, and others of the participating organizations, for their excellent assistance in the conduct of these tests and analyses of the data.

Appendix

The design characteristics of a ground fault compensating coil and the effect of such a coil on the magnitude and distribution of current under fault conditions, as compared to operating with the neutral isolated or grounded, may be determined analytically from a knowledge of the electrical characteristics of the transmission system.

PRINCIPLES OF GROUND FAULT COMPENSATION

It has been previously explained in this paper that a ground fault compensating coil consists of an inductance L which is designed to be connected in the neutral circuit of a system and tuned with the capacitance to ground C_G of the transmission circuits so that:

$I_L = I_{CG}$ and, neglecting losses
$I_F =$ zero

To accomplish this compensation of the ground fault current, the inductance L of a Petersen coil together with its associated transformer bank, and the capacitance to ground of the system, must be such that:

$$2\pi f L = \frac{1}{2\pi f C_G} \qquad \text{and}$$

$$\text{inductance} \quad L = \frac{1}{(2\pi f)^2 C_G} \text{ henries, and}$$

$$\text{inductive reactance } X_L = \frac{1}{2\pi f C_G} \text{ ohms} \tag{1}$$

where

C_G = zero sequence capacitance to ground of transmission system with one conductor grounded (farads)
f = frequency
I_{CG} = charging current to ground through capacitance C_G (amp)
I_L = current to ground through inductance L (amp)
I_F = fault current (amp)
L = zero sequence inductance of coil and transformer bank (henries)
X_{CG} = zero sequence capacitive reactance to ground of transmission system (ohms)
X_L = zero sequence inductive reactance of coil and transformer bank (ohms)
X'_L = inductive reactance of coil and transformer bank to residuals (ohms)
X_{Coil} = inductive reactance of coil alone (ohms)
$X_{Transf.}$ = inductive reactance of associated transformer bank (ohms)

With a Petersen coil connected in the neutral of a wye-delta transformer bank and considering the zero sequence network:

$$\text{Zero sequence reactance } X_L = 3X_{Coil} + X_{Transf.} \tag{2}$$

Viewed from the standpoint of reactance to residuals then:

Residual reactance $X'_L = X_{Coil} + X_{Transf.}/3$ (3)

$$X_L = 3X'_L \qquad (4)$$

In considering the application of such compensating coils to a system, the maximum and minimum lengths of line which are to be controlled by a single coil must first be decided. Then, after determining the capacitance to ground or the charging current to ground of these line sections, the inductance of the coil may be found. Knowing the wire size, configuration, spacing, height of conductors above ground, number of ground wires, etc., of the transmission lines, the capacitance between wires and ground may be determined by the formulas given by Clem[7] or by the method described in the article "Protection Against Earth Faults."[8]

TYPICAL EXAMPLE

For example, consider that it is desired to apply a Petersen coil to a 132-kv transmission system where the total length of line sections for a single coil will be between 75 and 150 miles and where the transmission line sections will consist of single circuit lines on steel towers with one ground wire, the conductors 3/0 copper with an equivalent spacing of 15 ft and at an average height of 40 ft above ground. The calculated zero sequence capacitance to ground C_G will be found to be 0.008 μf per mile

Capacitive reactance $X_{CG} = \dfrac{1}{2\pi f C_G}$ ohms (5)

$$X_{CG} = \frac{10^6}{(2\pi)60(0.008)} = \text{Approx. 330,000 mile-ohms (zero sequence)}$$

Charging current $I_{CG} = \dfrac{3E_N}{X_{CG}}$ amp (6)

$$I_{CG} = \frac{3\ (76{,}200)}{330{,}000} = 0.69 \text{ amp/mile}$$

Now assume further that the wye-delta connected transformer bank to be used with the coil is rated 132–13.2 kv, 15,000 kva and has an impedance of 200 ohms at 132 kv. The coil characteristics may then be determined as follows:

	75 mile	**150 mile**
$X_L = X_{CG}$ by eq 1	4,400 ohms (330,000/75)	2,200 ohms (330,000/150)
X_{Coil} by eq 2	1,400 ohms $(4{,}400 = 3X_{Coil} + 200)$	666 ohms $(2{,}200 = 3X_{Coil} + 200)$
Maximum coil Current $I_{Coil} = E_N/X'_L$	52 amps [76,200/(1,400 + 66)]	105 amps [76,200/(666 + 66)]
Voltage across coil = $(I_{Coil})(X_{Coil})$	72.8 kv (52 × 1,400)	69.4 kv (104 × 666)

A Petersen coil to be used in the neutral under such conditions therefore must have a reactance ranging from 666 to 1,400 ohms. The selection of coil taps or steps between these maximum and minimum reactance values will be governed by the intermediate lengths of line sections for which the coil is to tune.

A rough approximation of the required coil reactance may be obtained from the magnitude of the normal charging current to ground of the system on the assumption that the fault current is approximately equal to the charging current to ground under fault conditions. The current under fault conditions and neglecting corona, will be approximately 1.5 times the normal charging current to ground.[9]

Thus X_L (approx.) $= \dfrac{3E_N}{(\text{line length})(1.5)(\text{normal } I_{CG})}$ ohms (7)

For example the previously cited:

$$X_L = \frac{3(76{,}200)}{(150)\ 1.5\ (0.69)} = 1{,}470 \text{ ohms by eq 7, and}$$

$$X_{Coil} = \frac{1{,}470 - 200}{3} = 424 \text{ ohms by eq 2 for the 150-mile section}$$

CALCULATION OF FAULT CURRENT

Following the staged tests it was desired to study the magnitude and distribution of fault current analytically for the various operating conditions. The symmetrical component method of circuit analysis lent itself readily to this type of problem.[10] The following assumptions were made in connection with these calculations, based upon the experimental data obtained during the tests:

1. The capacitive reactance to ground X_{CG} of the Petersen coil system is equal in magnitude to the inductive reactance X_L of the Petersen coils together with their associated transformer banks, with the coils in tune (minimum fault current).
2. The fault current present on the Petersen coil system with a solid low resistance ground is due entirely to corona, neglecting other losses.
3. The corona voltage limit is exceeded by practically the same amount regardless of the fault location or the Petersen coil operating tap (within reasonable limits), i.e., the voltage to ground on the sound phases is unaffected by fault location or operating tap.

The calculation of the current during single-line-to-ground faults with Petersen coil or isolated neutral system necessitated consideration of a method for evaluating the component of the fault current due to the corona current to ground, i.e., a simple circuit representation which would simulate the effect of corona. The equivalent leakage resistance to ground representing corona was determined from the measured fault current by neglecting the positive and negative sequence impedances as follows:

Leakage resistance $R_G = \dfrac{E_R}{I_F \cos\theta}$ ohms (8)

where

E_R = residual voltage = $(3E_N)$ volts
I_F = fault current amp
θ = phase angle between fault current $-I_F$ and residual voltage E_R

This method is not strictly true since it neglects the effect of other resistance in the circuit. However, it was found sufficiently accurate for this purpose. This leakage resistance for use in the equivalent zero sequence network has been considered to be in parallel with the capacitive reactance to ground of the system.

The specific values of circuit constants used in the analytical study are shown in Table VII.

SOLUTION OF NETWORKS

The procedure followed in analyzing the Petersen coil, isolated neutral, etc., systems, was to set up the positive, negative, and zero sequence networks in ohms on a common voltage base and then to solve these networks in the customary manner[10]. Starting at the most remote points the impedances were combined up to the point of fault using delta-wye transformations where necessary. In the zero sequence network it was recognized that the capacitances to ground of the various line sections may be united at a common point (ground). After the positive, negative, and zero sequence impedances at the point of fault had been determined, the fault currents were found by the following formula:

$$I_F = \frac{3E_N}{Z_1 + Z_2 + Z_0 + 3R_F} \text{ amp} \qquad (9)$$

Table VII—Summary of Test System Characteristics, One Conductor Grounded

Neutral Connection	Petersen Coil	Isolated Neutral	Directly Grounded	Neutral Resistance
Capacitance to ground C_G μf/mile/phase	0.01	0.01	0.0088	0.01
Capacitance reactance X_{CG} mile-ohms	265,000	265,000	300,000	265,000
Charging current I_{CG} amps/mile	0.92	....	0.81	0.92
Leakage resistance due to corona R_G mile-ohms/phase	1,370,000	750,000	Considered zero	1,370,000

where

E_N = normal line-neutral system voltage (volts)
I_F = fault current (amp)
R_F = fault resistance (ohms)
Z_1, Z_2, Z_0 = positive, negative, and zero sequence impedances, respectively, at the point of fault (ohms)

When the system is grounded by means of a Petersen coil the sum of the positive and negative sequence impedances ($Z_1 + Z_2$) is small compared with Z_0 and therefore it may be considered that:

$$I_F = \frac{3E_N}{Z_0} \text{ approx. amp.} \tag{10}$$

With the neutral of the system isolated the only path for the fault current was through the distributed admittance to ground of the transmission system. The current was therefore a maximum at the point of fault and decreased uniformly along each circuit away from the fault. The solution of the networks and the calculations of the fault current in this case were made similarly to those previously described, using the proper values for the circuit constants. The analysis of the sequence networks and the computations of fault current with the system neutral grounded directly by the transformer bank at Saginaw were made in the manner customary for grounded neutral systems.

An example of the solution of the networks for a solid low resistance fault at Saginaw with the Petersen coil system may serve to make this procedure clear. The positive and negative sequence networks for this example are shown in Fig. 2 and it will be noted that the positive and negative sequence impedances at the point of fault consist only of the Saginaw generator and the 45,000-kva transformer bank. The equivalent zero sequence network is illustrated in Fig. 13. The zero sequence impedance of each circuit at the point of fault was found by combining the impedances (using complex notation) from the remote end in toward the Saginaw bus. These impedances were then combined as indicated in Table VIII.

The solution of the network between Emery Junction, Loud, and Foote was accomplished by first transforming the series impedances of the lines from their delta connection to an equivalent wye. In a similar manner the delta mileage was transformed into an equivalent wye mileage and the mileage of each branch of the wye was then multiplied by the ratio of the total delta to the total wye mileage so as to make the total mileage of the wye equal to the original total mileage of the delta. The capacitive reactance and the leakage resistance per mile were divided by the corrected wye mileages and the resultant impedances considered concentrated at the mid-points of the wye branches of the series impedances. This was an approximation, but it was sufficiently accurate because the series impedances were small compared with the shunt impedances.

DISTRIBUTION OF FAULT CURRENT

The distribution of fault current in the various circuits was determined by starting at the point of fault where the zero sequence impedance looking in each direction was known, and computing the currents in each branch at that point which add up to equal the total fault current. The product (fault current × total zero sequence impedance looking in at the fault) equaled the product (residual current in each branch × zero sequence impedance of that branch looking at the point of fault). The zero sequence impedance at each point of discontinuity in the network had previously been computed and the currents in each of the other branches therefore could be readily determined. In Fig. 14 is shown the calculated distribution of residual current for a single-line-to-ground fault at Saginaw with the Petersen coils in tune.

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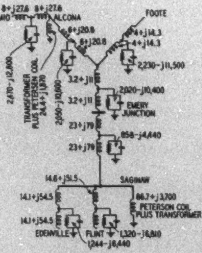

Fig. 13. Equivalent zero sequence network for determining impedance for fault with the Petersen coil system

Impedances expressed in ohms on 140-kv base
Equivalent corona leakage resistance = 1.37 × 10⁶ mile-ohms per phase
Capacitance to ground = 0.01μf per mile per phase

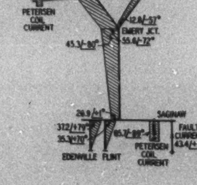

Fig. 14. Calculated values of residual current distribution for fault at Saginaw during 140-kv Petersen coil tests

Calculated fault current = 43.4 amp
Measured fault current = 38 to 43 amp

Table VIII—Fault Current Calculations, Petersen Coil System, With Fault at Saginaw

Section	Petersen Coil System (Taps *S4*, *A8*)
Positive Sequence Network	
Saginaw generator	0 + j146 ohms
Saginaw transformer	5.3 + j 48 ohms
	Z_1 = 5.3 + j194 ohms
Negative Sequence Network	
Consider $Z_2 = Z_1$	Z_2 = 5.3 + j194 ohms
Zero Sequence Network	
Avg fault current I_F	40 amp
Leakage resistance R_G (eq 8)	6,080 ohms
Leakage resistance (6,080 × 226)	1,370,000 mile-ohms
Saginaw coil & transf. residual react. X'_L (eq 3)	1,080 ohms
Alcona coil & transf. residual react. X'_L (eq 3)	623 ohms
Equiv. coil & transf. residual react. X'_L (eq 3)	395 ohms
Equiv. coil & transf. Zero Seq. React. X_L (eq 4)	1,180 ohms
Capacitance C_G (eq 1)	0.01 μf/mile
Cap. react. X_{CG} (eq 5)	265,000 mile-ohms
Charging current I_{CG} (eq 6)	0.92 amp/mile
Mio line at Alcona	2,430 − j12,800 ohms
Alcona coil and transformer	24.4 + j1,870 ohms
Alcona at wye tap	309 + j2,710 ohms
Foote at wye tap	2,230 − j11,500 ohms
Alcona and Foote at wye tap	710 + j3,430 ohms
Au Sable line at Saginaw	8,280 − j2,370 ohms
Edenville line at Saginaw	1,260 − j6,380 ohms
Flint line at Saginaw	1,340 − j6,760 ohms
Saginaw coil and transformer	86 + j3,250 ohms
Total Z_0 at Saginaw	Z_0 = 5,580 − j606 ohms
Total $Z = (Z_1 + Z_2 + Z_0)$	Z = 5,590 − j218 ohms
Fault current I_F (eq 9)	43.4 ∠4 deg amp

An Experimental Ignitron Rectifier

Experiments aimed at the elimination of the backfire tendency of arc-rectifiers have led to a device termed the "ignitron." Equipment, methods, and test data are discussed in this paper.

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DURING the early development of the mercury arc rectifier, the serious defect in its operation known as backfire or arc-back, quickly became apparent. These erratic failures, amounting to complete loss of valve action of the device, necessitated a large expenditure of effort on the part of engineers and physicists before practical rectifiers could be built. At the present time entirely satisfactory rectifiers are available commercially, but the problem of backfire continues to hamper the designer. Grids, shields, disadvantageous spatial relationships, costly anode constructions, force their way into his structures because reliable valve action requires them. To make clear the advantages in these respects of the apparatus described, a brief summary of the factors affecting backfire is given.

Many investigators[1] have associated the backfire or accidental formation of a cathode spot on the anode, when it is bearing negative voltage with the back current. By back current, one means the positive ion current collected by the anode bearing negative voltage, as a result of diffusion of ions to the anode region, or as a result of a self-maintained discharge of the glow type. Slepian and Ludwig[2] defined the conditions favorable for backfire and cited experiments made by D. E. Marshall in which backfires were produced by striking a negative electrode with some kind of small particle. It was found that backfires would result only if ionization existed, causing back current to the negative electrode.

In the normal multi-anode rectifier this back current may arise in 3 ways:

1. Throughout the nonconducting period of a particular anode there is a continuous back current flow to it as a result of diffusion of ions from arcs to other anodes in the same tank, which are active during this period.

2. Immediately following the "transition point" that is the point at which the current reaches zero and negative voltage is applied rapidly to the anode, a very high initial back current will flow for at least a short time because of the high density of ionization present in the anode region due to current flowing just previous to this transition point.

3. In case conditions become such that a self-maintained glow discharge can exist with its cathode upon the negative anode, then a comparatively high back current can exist for a long period of time.

The vapor density of the mercury in the vicinity of the anode also has been found to have a considerable effect on the backfire probability. This effect is not necessarily distinct from the association of backfire probability with back current, because clearly the transition back current just described as well as fulfillment of the condition under which a self-maintained glow may exist, largely depends upon the vapor density.

In any practical rectifier a self-maintained discharge during a nonconducting period may be avoided by holding the gas density and the dimensions of the rectifier within limits such that the available voltage will not maintain the discharge. Furthermore, the length of time during which the transition back current will flow may be minimized by keeping the gas density low so that the residual ions will be lost rapidly by diffusion. It also is possible to minimize the continuous diffusion back current by surrounding a negative anode with shields and grids and by placing it far away from other conducting arcs. The shields and grids also are effective with respect to the other 2 forms of back current.

Such an analysis shows why multi-anode rectifiers have been designed having rather large dimensions, necessitated by a tortuous arc path, grids and shields, large internal coolers and in fact all those factors of design which prevent the use of a simple conducting arc having a low drop, and which consequently causes the rectifier to be expensive and inefficient compared with what might be expected if backfires could be avoided in a more direct manner.

In order to keep the average backfire rate of a rectifier low and at the same time to use a small structure in which the anode is placed directly above the cathode without interfering grids and shields, more suitable means are required for keeping the back current sufficiently low. These desirable characteristics are attainable readily in the following way:

If a rectifier having a single anode and mercury pool cathode within a separate small tank were to be built, no continuous back current could flow to the anode when it is negative, because the tank would contain no source of ionization and would remain entirely inactive during the nonconducting period. However, some means for restarting the arc would be required when the device is to become conductive again. A continuously burning "keep-alive" would be satisfactory for restarting the arc, but it would completely defeat the purpose, which is to avoid any source of ionization during the period of nonconduction. An intermittent "keep-alive," or "make-alive" is required. An entirely suitable ignition means has been described by Slepian and Ludwig,[3] and it can be

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[1] For numbered references see end of paper.

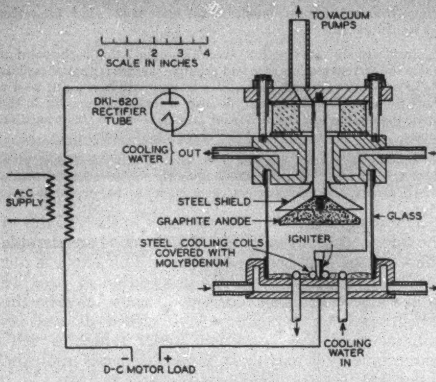

Fig. 1 A single anode experimental ignitron

used in the single anode tanks without causing continuous back current.

Thus the continuous back current need be of no more concern, but to obtain backfire immunity a self-maintained glow discharge also must be avoided during the nonconducting period. Furthermore it is essential rapidly to deionize the gas space between the electrodes at the transition interval. Sufficient and proper cooling alone, has been found adequate to accomplish both of these purposes.

Thus one is led to the adoption of single anode tanks, properly cooled and with built-in igniters, to escape the complexity and comparative inefficiency of the conventional rectifier. The new structure has been termed an "ignitron."

EXPERIMENTS WITH SMALL IGNITRONS

The essential components of a small ignitron are shown diagrammatically in Fig. 1. The anode was made of graphite and placed 2 in. above a mercury pool cathode. For experimental purposes the side wall was of pyrex glass sealed to the cathode and to the anode structure. The anode was insulated from the plate sealed to the top of the glass by porcelain. Rubber gaskets were used to secure vacuum tightness at the junction of the porcelain and the iron and the upper part of the assembly were bolted together. The upper end of the igniter was connected to the cooled upper plate, which was connected electrically to the anode through a rectifier tube. This unit was tested in a single-phase half-wave rectifier circuit and the output direct current power was supplied to a rotating machine. Tests were made at 300 volts and 50 amp direct current. During these initial tests no special cooling was used, the cathode itself and the upper plate served entirely for condensation of the mercury evaporated at the cathode. During the initial tests several backfires occurred. It was interesting to note, however, that none of these backfires seemed to be associated with mercury drops thrown from the cathode against the anode, or mercury drops falling from the anode when it was run cold. In the usual type of rectifiers such conditions would cause practically continuous backfire, because almost every drop impinging against the anode would produce an arc back immediately. This observation seems to bear out the previous test obtained by D. E. Marshall which requires back current in order for impinging particles to produce backfire, and at the same time these particles show that throughout most of the nonconducting period the back current in this ignitron must have been quite small.

In another ignitron similar to the one described, except larger, tests made by Dr. D. Silverman indicated that the backfires obtained did occur at the transition interval. The circuit used for these tests was the same as that shown in Fig. 1 except that a condenser was connected in parallel to the ignitron. This condenser was sufficiently large so that approximately 400 microseconds was required before it could be charged to a potential greater than 100 volts by the current flowing into it through the reactance placed in series with the ignitron. Consequently negative voltage was not impressed suddenly on the ignitron anode as is usual in case of a rectifier circuit. During the test made with the condenser, no backfires occurred, although the backfire rate was very high with the same current and voltage when the condenser was removed. The fact that both of these ignitrons operate backfire free in a single phase circuit when a resistance load is used also indicates that the backfires are occurring in the transition region because the negative voltage is applied slowly to the anode with the resistance load and the ions have ample time practically to vanish before considerable voltage is present.

During tests with the ignitron shown in Fig. 1, it was found that if the temperature of the ingoing cooling water was increased from 18 to 30 deg C the backfire rate would be increased very considerably. At the same time a glow could be detected during the nonconducting period by looking into the vessel through a stroboscope. At the lower water temperature no light at all was visible during a nonconducting period.

In order to make the device less critical to ingoing water temperature and also to improve conditions at transition, a special cathode cooling means was de-

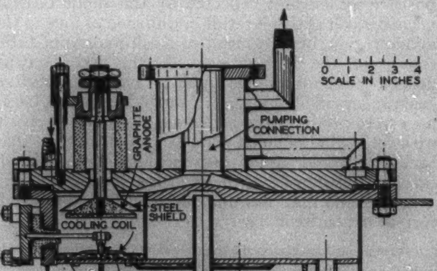

Fig. 2 Section of a 6-anode polyphase ignitron

vised. This consists in fixing the cathode of the arc directly on a cooling coil. Actually iron pipes arranged to carry water were covered with molybdenum and placed in the cathode such that the mercury level extended about half the height of the pipe. It may be seen from this construction (shown in Fig. 1) that approximately half the cooling coil extends above the mercury. The igniter, which in this case is a crystal of carborundum, is so placed as to touch this cooling coil at one particular spot along this length. The igniter also is surrounded completely with a glass covering except for a vertical strip of its outer surface which contacts with the mercury and the spot fixing coil. In this way the arc is started directly on the well cooled fixer.

During tests with this arrangement it was found that 50 amp at 600 volts direct current machine load was carried for one week without backfire. Ingoing water temperature during this test was 27 deg C. The arc drop as observed from an oscillogram had an average value somewhat less than 10 volts.

A still further check on the applicability of the ignitron principle to rectifiers was made by building another unit similar to the one shown in Fig. 1, but with the following changes. The glass walls and steel cathode structure were replaced by a steel cup so that the walls as well as the cathode could be cooled. The cooling coils in the cathode were omitted. A hollow iron anode insulated from the walls and cathode by glass sealed to 2 pieces of "kovar" (an iron alloy, developed by H. Scott, which may be sealed to glass) was used instead of graphite. The igniter lead was brought in through the side by means of another kovar-glass seal. The physical dimensions of this unit essentially were the same as those of Fig. 1. With this ignitron it was possible to supply a rotating machine load of 50 amp average and 600 volts direct current through a half wave rectifier connection for 19$^1/_2$ hours without backfire. With an average of 75 amp and 600 volts dc supplied for 15$^1/_2$ hr, only 3 backfires occurred. It was possible to carry this load in the absence of cooling coils in the cathode because of the much more effective cooling obtained with steel walls. Another factor which aided in giving satisfactory operation of the ignitron was the fact that this unit practically had no leaks. The gas pressure rose only about 2 microns an hour with the unit trapped off and carrying a 50-ampere d-c load. The arc drop again was slightly under 10 volts.

These tests seem to show that with sufficient cooling to avoid a self-maintained glow and to speed up the deionization at the transition, the ignitron principle may be adapted to rectification with results vastly improved over any present form of mercury pool cathode device.[4]

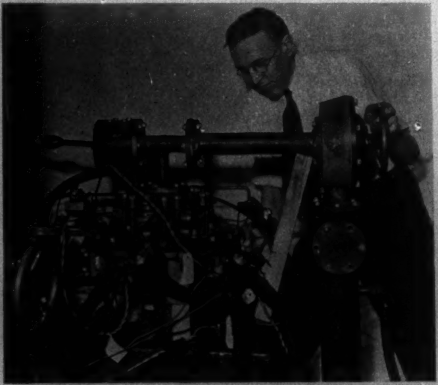

Fig. 3 View of polyphase ignitron

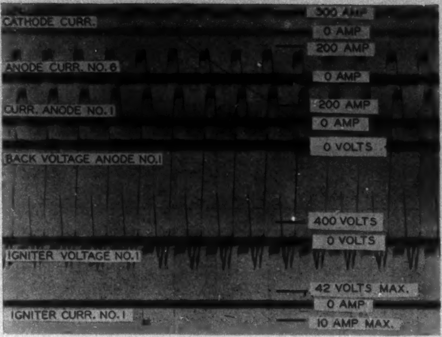

Fig. 4 Oscillogram showing typical ignitron operation for double 3-phase connection; motor load 320 amp at 260 volts

THE POLYPHASE IGNITRON

In following up this idea a polyphase ignitron was built for test in a 6-phase or double 3-phase circuit. This experimental ignitron shown in Fig. 2, consists of 6 units each similar to the ignitron in Fig. 1, except that the glass wall is replaced by steel. The 6 units are mounted in a steel tank which provides a common water-cooling system for the walls and another for the cathodes and a common evacuating system. This assembly is very compact. It is only 9$^1/_4$ in. high and 16 in. in diameter. There is no need for insulating the cathodes or restricting the motion of the cathode spot. At the beginning of every cycle the arc starts always at the igniter and tends to fix on the molybdenum covered cooling pipe. Rarely does it move more than 1$^1/_2$ in. from the igniter. All the cathodes are interconnected to permit free flow of mercury from one pool to another, assuring equal distribution of mercury among the 6 pools.

This ignitron was operated in 2 types of rectifier circuits—a double 3-phase of the usual kind and a 6-phase obtained by short circuiting the interphase transformer.

Figure 4 shows a typical oscillogram taken when the rectifier was supplying 325 amperes at 265 volts direct current. The total cathode current as indicated by this oscillogram has more of a ripple than is permissible with commercial rectifiers since no reactor was placed in the cathode lead to provide smoothening. The condition in which 2 anodes are carrying current at the same time is shown clearly. It can be seen readily that after a conduction period, the voltage rises suddenly to about 300 volts which is typical of power rectifier circuits. Also it can be seen that the voltage required to strike an arc in the rectifier by means of the igniter is only slightly more than 40 volts and that the maximum current required is only about 10 amperes. The time of application of this voltage and current is very short being only about 3 per cent of a cycle or about 10 electrical degrees. The average current through the igniter is somewhat less than 0.1 ampere, consequently the power input is very low.

Figure 5 shows the nature of the arc drop. The process of measuring it necessitated putting a rectox unit in series with the oscillograph element, hence the deflection is not linear nor is it the same on both sides of the zero line. It can be seen though that the average arc drop is slightly more than 9 volts.

At the time of writing, this ignitron had been operated for more than 49 hours in a 6-phase circuit supplying 300 amperes at 300 volts dc or 90 kw to a rotating machine load. During this time no backfires occurred nor was there any other indication that the unit had reached its maximum capacity. These tests still are in progress, but the data obtained thus far in actual rectifier operation seem to demonstrate that the ignitron is quite practical.

The authors wish to acknowledge the creative guidance of Dr. J. Slepian in the development which has been described and to credit him with many contributions fundamental to the ignitron.

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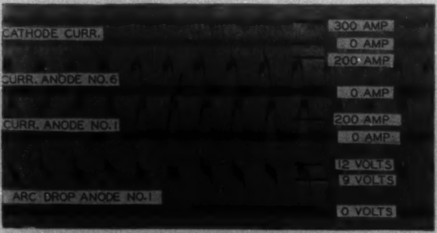

Fig. 5 Oscillogram showing ignitron arc drop for double 3-phase connection; motor load 325 amp at 260 volts

Inductor Alternators for Signaling Purposes

Recent developments of the inductor alternator for the generation of modulated high frequency currents for telephone or telegraph signaling or carrier purposes are given in this paper. Several novel arrangements of the electric and magnetic circuits and certain principles and special details of design and construction are described.

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GENERALLY speaking, inductor alternators designed for the generation of special tones for signaling or telegraph carrier purposes on communication lines are of small output, ranging from a few hundredths of a watt to 40 watts, and in frequency from about 135 cycles to 2,300 cycles, for the uninterrupted or pure tones. These tones may be used in their pure form for certain applications, or may require modulation at some low frequency rate for the production of other characteristics. In some cases it is desired to interrupt the tone completely at some such rate as 20 or 30 cycles; and again the signal may require only the variation of the voltage or amplitude of the high frequency current at a periodic low frequency rate without complete interruption.

It is not the function of this paper to discuss the applications of these tones in detail, as that phase of the subject is outside the experience of the author, but some of the applications are mentioned to establish a practical connection.

In leading up to the special designs required for the production of the interrupted, or otherwise varied, tone signals it is essential first to understand the general type of inductor alternator that has been found most suitable in these small sizes for the generation of uninterrupted high frequency currents. These simpler machines are interesting in themselves, illustrating as they do the fundamental principles of generation, and an arrangement of parts which is capable of modification to produce the more complicated designs which are the principal subject of this paper. In this connection an arrangement of especial interest is described in which 12 plain inductor alternators each giving a different fre-

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quency, are assembled into a single "multifrequency" unit which has to meet very exacting requirements for both voltage and frequency.

In addition to its superiority as a generator of the higher frequencies the inductor alternator has several other advantages.

1. It has no moving conductors.
2. It requires neither brushes nor collector rings.
3. It can be operated at a higher flux density for a given core loss because the flux does not reverse but merely rises and falls between maximum and minimum values.
4. It can be operated at higher speeds because there is no winding on the rotor.
5. It has a lower cost of attendance and maintenance due to the absence of brushes and collectors.
6. It can be designed for the *direct* generation of interrupted or modulated high frequency output.

FREQUENCY RANGE OF FRACTIONAL HORSEPOWER INDUCTORS

The expression "high frequency" is relative, and as used in connection with the subject matter of this paper is defined as any frequency high enough to warrant the construction of an inductor alternator in preference to the conventional type of salient pole a-c generator. Due to the small physical size of fractional horsepower frames, it is surprising how low this so-called high frequency may be and still meet the above definition.

Standard fractional horsepower d-c motors are bipolar, hence revolving armature type a-c generators built in these frames also are bipolar. The larger induction motor stators are slotted so as to permit 4, 6, and 8 pole windings, and presumably revolving field rotors could be built up to 8 poles for use with these stators. As a matter of fact, however, a 6-pole field design is about the economical limit for the largest fractional horsepower frame, and it is preferable, when considering the next step, to use an inductor alternator having a 4-tooth rotor instead of a revolving field system having 8 poles.

Either the 8-pole alternator or the 4-tooth inductor generator would give 120 cycles at 1,800 rpm but the ampere turns per pole permissible in the restricted winding space of the 8-pole revolving field system would be considerably less than those obtainable with the bipolar stator excitation of the 4-tooth inductor alternator. For this reason the air gap flux density of the inductor machine would be enough higher than that of the 8-pole revolving field alternator to make it preferable from an output standpoint, if for no other reason. Therefore, 120 cycles at 1,800 rpm may be taken as approximately the correct point in fractional horsepower frames to change over from the conventional a-c generator to the inductor alternator. For frames of larger size this change-over point would occur at a higher frequency, the value of which would continue to rise with the absolute size of the machines under consideration.

The approximate upper limit of frequency obtainable in fractional horsepower frames with the type of construction described is between 4,000 and 5,000 cycles at 1,800 rpm giving a practicable frequency range, *at a definite speed*, for inductor alternators in these small sizes of about 40 to 1. The speed of 1,800 rpm, is, of course, low for such small frames, and with proper design and construction may be increased 4 times, giving an absolute upper frequency limit of 15,000 to 20,000 cycles for these small machines.

The power output, of course, drops off at the higher frequencies but can be maintained very well up to the upper limits given by suitable tuning of the output and by the proper choice of materials.

CONSTRUCTION—ELECTRIC AND MAGNETIC CIRCUITS

The fractional horsepower inductor alternators usually are designed as indicated in Fig. 1.

The coils in which the high frequency a-c output is generated are wound around the 12 stator teeth as shown and all connected in series so as to add their voltage, terminating in leads L_1 and L_2. The excitation is bipolar and is provided by the 2 field coils on the stator element terminating in leads F_1 and F_2. The exciting flux passes from the 6 stator teeth of 1 polar group through the rotor into the teeth of the opposite polar group and returns by way of the 2 halves of the yoke, the magnetic circuit being, in this respect, exactly like that of any 2-pole generator.

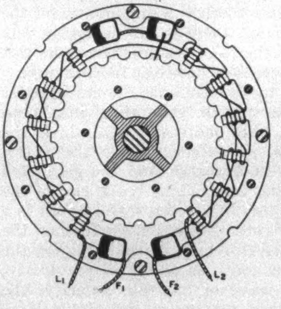


Fig. 1. Cross section of stator and rotor assembly, showing arrangement of teeth and windings of a typical inductor alternator for generating uninterrupted current—illustrating fractional pitch of stator teeth

In the alignment of stator and rotor teeth in Fig. 1, there are $1^1/_2$ rotor tooth pitches for 1 stator tooth pitch. With an *even* number of stator teeth in each exciting polar group this *fractional* pitch alignment places half of the stator teeth directly in line with rotor teeth and the other half in line with rotor slots. The stator teeth in line with the rotor teeth carry *maximum* flux, those in line with the rotor slots carry *minimum* flux. If the rotor is revolved one half a rotor tooth pitch the flux shifts in half the stator teeth from maximum to minimum and in the other half from minimum to maximum. The total flux, however, which passes through the field coils and around the yoke remains *constant*. Therefore, in the construction shown in Fig. 1, which is fundamental for all of the fractional horsepower frame inductors, constancy of the main exciting flux through the field coils and yoke is secured by means of: (1) an even number of stator teeth per exciting polar group and (2) stator teeth spaced a *fractional* number of rotor tooth pitches apart.

In general, with this fractional pitch as a basis of design, the stator teeth may be spaced, $^1/_2$, $1^1/_2$, $2^1/_2$, $3^1/_2$, etc., times the rotor tooth pitch. The higher the frequency and the finer and more numerous the rotor teeth, the larger would be the number of rotor tooth pitches that would have to be allowed for one stator tooth pitch in order to secure sufficient winding space for the a-c generating coils. The number of stator teeth, however, affects only the total voltage generated, while the frequency depends wholly upon the *rotor tooth pitch* and the speed of the rotor.

It should be noted also that the arrangement of teeth shown in Fig. 1, in which half of the teeth are in the position of maximum flux while the other half are in the position of minimum flux, is equivalent to displacing half of the stator coils 180 elec deg with respect to the other half. As a result of this connection all even harmonics cancel out, but the fundamentals add. For this reason a fractional pitch arrangement of the stator teeth as shown gives a much better wave shape than would be obtained by an integral pitch spacing even if this latter were not objectionable from the standpoint of pulsating the main exciting flux through the field coils.

Frequency. When any rotor tooth exactly is in line with a stator tooth, the flux through the a-c coil around that stator tooth is a maximum and the voltage is zero, because there is no change in flux at that instant. As the rotor tooth moves from this position, the flux decreases, slowly at first, then very rapidly as the rotor tooth completes the first quarter of its full pitch movement generating maximum voltage in the coil, then more slowly, and, as the center of the rotor slot comes under the stator tooth, the decrease in flux ends and the generated voltage again becomes zero. This is the end of the first half cycle and the flux in the stator tooth is a minimum. As the rotor tooth moves further the flux increases at a varying rate, depending upon the exact position of the tooth as described previously, generating the a-c wave of opposite polarity, the flux again becoming a maximum and the voltage zero when the next rotor tooth exactly comes in line with the original stator tooth.

Therefore, *one cycle* is completed for a movement of *one* rotor *tooth pitch.* If the rotor has a *full number* of *equally spaced* teeth uniform frequency will be generated.

If

f = frequency in cycles per second
P = number of rotor teeth in full circumference
S = revolutions per second.

Then

$$f = PS$$

If P = the number of poles of a revolving field system, then $f = \frac{P}{2} \times S$. Hence one inductor rotor tooth is equivalent in frequency generation to a pair of poles of the conventional type alternator. Another thought is that one inductor rotor tooth pitch = 360 elec deg, whereas, a pole pitch of the conventional type alternator field = 180 elec deg.

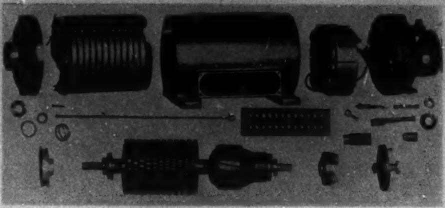


Fig. 2. Component parts of a multifrequency set

Voltage. The voltage of the entire a-c winding is proportional to the rate of change of flux and to the number of turns in series. The flux change per stator tooth is equal to the difference between the maximum and the minimum flux in the 2 extreme positions of the rotor tooth as described. This difference in flux per *stator* tooth is called the "useful flux."

If

T = total turns in series on *all* stator teeth
ϕ = useful flux per stator tooth
E = effective voltage generated in entire a-c winding.

Then

$$E = 2.22 f \phi T 10^{-8}$$

The derivation of this formula is not given, as this may be obtained from various textbooks on the subject.

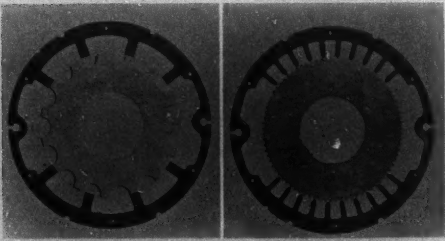
It is easy to assign definite values to all of the terms of the above voltage formula except ϕ. The determination of this useful flux is important and somewhat difficult. It may be found, however, within a fair degree of accuracy, by means of large scale flux plots of the teeth in the maximum and minimum positions. It should be noted that such determinations will be less accurate in the case of the higher frequency inductors having narrow tooth widths and relatively large values of minimum flux. The useful flux then is equal to the difference between 2 relatively large quantities, and small errors in the determination of either one of these, causes a much larger percentage of error in their difference.

Percentage Rotor Tooth Width. The graphical method of determining the useful flux just referred to assumes that the dimensions of the rotor and stator teeth already have been established. The choice of these dimensions, however, must very carefully be made, particularly the width of rotor tooth as compared to rotor tooth pitch. In starting with a very narrow rotor tooth, say 20 per cent of the tooth pitch, the maximum flux and the useful flux both will be quite small. As the percentage tooth width is increased (the stator tooth being kept the same width as the rotor tooth), both the maximum and useful flux increase up to a certain point. If the tooth width is increased still further the maximum flux continues to increase but the useful flux begins to decrease, because the *minimum flux* now is increasing faster than the maximum flux causing the difference between the 2 values—the useful flux—to diminish. When designing an inductor alternator care should be taken to choose a width of tooth that will give the greatest value of useful flux.

Saturation. In the graphical determination of the useful flux it has been assumed that there is no rotor or stator tooth saturation. If the ampere turns of an inductor alternator (similar to Fig. 1) are increased, and the yoke section is heavy enough so that saturation occurs first in the stator or rotor teeth, the "maximum flux" will be held at a certain point by this saturation while the "minimum flux" will continue to increase, as neither the rotor nor stator teeth will saturate in the minimum position, the extra ampere turns all being absorbed in the large gap. The result of this is a decrease of useful flux and of generated voltage. A saturation curve taken on an inductor alternator with this kind of a magnetic circuit will show increasing no-load voltage with increasing field current up to a certain point, beyond which the generated voltage will decrease with increased excitation. This same effect also is noted in the paper, "A 10-kw, 20,000-Cycle Alternator," by M. C. Spencer, JL. OF THE A.I.E.E., July 1927, p. 681. This puts a definite limit on the amount of voltage that can be obtained by field control. This condition of tooth saturation generally should be avoided, and if saturation must be had in order to minimize the effect of varying exciting voltage, temperature changes, etc., on the generated voltage, it would be better to saturate the yoke in the constant flux zone and thus retain some field control to cover manufacturing variations among individual machines. Locating the saturated section of the magnetic circuit in the constant flux zone also prevents the excessive iron losses that might occur if this section were subject to the same high frequency variations which occur in the stator and rotor teeth.

THE MULTIFREQUENCY SET

The multifrequency set shown disassembled in Fig. 2, is an inductor alternator generating 12 fundamental frequencies at the same time. The generator end really is 12 inductor alternators combined into 1 unit. The 12 stators differ in mechanical details, and have different windings, but all are assembled in 1 block, and excited by a common set of field coils. Each stator is composed of the same number of silicon steel punchings so that the axial length is the same for each unit. Different punchings, however, are required for the respective stators. These stator elements are separated axially by nonmagnetic (brass) spacers to prevent frequency interference between adjacent channels. The block of 12 stators with windings complete is assembled in an aluminum case, it not being permissible to use a cast iron case on account of frequency interference.



Figs. 3 and 4. Stator and rotor punchings of a multifrequency set; (left) 15-tooth rotor channel, and (right) 81-tooth rotor channel

The assembled rotor is composed of 12 different rotors, mounted on a brass spider and separated by brass spacers. This assembled rotor is mounted on the shaft so that its respective channels line up exactly with the corresponding stator channels. The number of rotor teeth begins with 15 and proceeds upward by arithmetical progression, having a common difference of 6, until the highest number of teeth, 81, is reached. Figs. 3 and 4 show the stator and rotor punchings of the 15 tooth and 81 tooth channels, respectively. This inductor is built into a 2 bearing set having a 20/24-volt d-c speed-regulated motor as the other unit. The rating of each channel is 0.7 volt, 0.04 amp—the frequency ranging from 425 to 2,295 cycles at a speed of 1,700 rpm. The speed is held within about plus or minus $^1/_2$ per cent by the centrifugal speed regulator for the above battery range and for all variations of load and temperature.

The multifrequency sets are used for sending telegraph messages on the longer lines, such as those between Boston, New York, Chicago, and the West Coast. These machines make it possible to send 12 messages over 1 circuit at the same time, filters being used to tune in the messages at the receiving end.

The first model multifrequency sets were designed by H. M. Stoller of the Bell Telephone Laboratories and built in New York under his supervision.

FIRST METHOD OF PRODUCING INTERRUPTED SIGNALING CURRENTS

In 1922 a demand arose for a special 1,000-cycle signaling tone for use on long telephone toll circuits. The customer's specification requested a speed-regulated, battery-driven, 2-bearing set, the inductor alternator of which should generate 1,000 cycles, and be fitted with a mechanical interrupter which would interrupt completely the 1,000-cycle tone at a 20-cycle rate, that is, $^1/_{40}$ sec on, $^1/_{40}$ sec off. The 1,000-cycle signaling pure tone also was required for testing purposes in carrier systems. This set originally was known as the "voice frequency signaling set." A schematic diagram of the set with its d-c speed regulated motor, and mechanical interrupter is shown in Fig. 5. It will be noted that the inductor alternator generates an uninterrupted current, which is interrupted by 2 mechanical interrupters so as to supply the 1,000/20 tone to 2 independent circuits. Oscillograms of the pure tone and of the interrupted tone from this type of set are shown in Fig. 6. A disassembled view of the set, Fig. 7, clearly shows the inductor and mechanical interrupter parts. Several of these sets were manufactured and gave good service except that the interrupter rings and brushes required considerable maintenance and the efficiency was not good due to the friction loss of the 6 interrupter brushes. The rating of the generator end of this set is 6 volts, 0.035 amp, 1,000 cycles, 1,175 rpm, ± 2 per cent. The inductor rotor has 51 teeth. (19.6 rps × 51 = 1,000.)

Direct Generation of Interrupted Currents

As stated previously: "one *cycle* is completed for a movement of *one rotor tooth* pitch. If the rotor has a *full number* of *equally spaced* teeth, uniform frequency will be generated."

After a few of the mechanically interrupted sets had been built the idea was conceived that it would be possible to generate the 1,000-cycle tone for half the time by using a rotor having one-half of the circumference smooth and the other half notched with teeth of the same circumferential pitch as that of the 51 tooth rotor of the original set. This idea was tried out and found to work perfectly. As a result, it was possible to eliminate the entire interrupter of the original set, reduce the first cost, eliminate maintenance of the mechanical interrupter and increase the efficiency. Fig. 8 shows the disassembled view of this new type of set. Comparing this with Fig. 7 it will be noted that only 3 brushes are required instead of the 9 brushes used on the original set. The stacking of the partly toothed rotor has been increased to raise the flux per stator tooth to make up for the fact that the number of teeth available for the generation of voltage has been reduced from 12 to 2.

Fig. 9 shows a cross section view of this special inductor. Comparing this with Fig. 5 it will be noted that the winding L_1, L_2 supplies interrupted circuit No. 1 and winding L_3, L_4 supplies interrupted circuit No. 2. By connecting L_1, L_2, L_3, and L_4 in series an approximately continuous 1,000-cycle tone is generated, each winding supplying this tone for half the time. Fig. 10 shows 3 oscillograms taken from this first machine. Oscillograms 1 and 2 show the result of connecting the 2 interrupted windings in series. In oscillogram 1 the overlapping portions of the active generating periods of the 2 windings add their voltage, while in oscillogram 2 these overlapping portions are in opposition. Oscillogram 3 is representative of either one of the interrupted circuits taken alone. This signal, while not so sharply interrupted as some which have been produced by inductors of later design, proved to be an entirely satisfactory substitute for the mechanically interrupted pure tone.

Examination of Fig. 9 shows that in this first attempt to generate an interrupted current the stator teeth were spaced $2^1/_2$ rotor tooth pitches apart. The rotor has 25 teeth and 26 slots on half the circumference (equivalent to 52 teeth and 52 slots for a full circumference). When this type of rotor is revolved at 19.23 rps, 1,000 cycles are generated in each alternate circuit for one-half the time. It is evident, therefore, that the generated frequency is not equal fundamentally to the number of teeth on the rotor multiplied by the revolutions per second, but that it is equal to the peripheral velocity of the rotor surface in feet per second, divided by the circumferential pitch of the rotor teeth in feet (any other units of length or angle may, of course, be used).

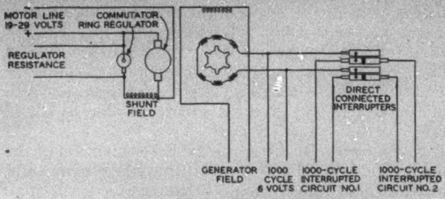


Fig. 5. A 1,000-cycle voice frequency signaling set of mechanical interrupters

Fig. 6. Oscillograms of the tones of the set shown in Fig. 5

(Above) 1,000 cycles uninterrupted
(Below) 1,000 cycles interrupted at 20-cycle rate

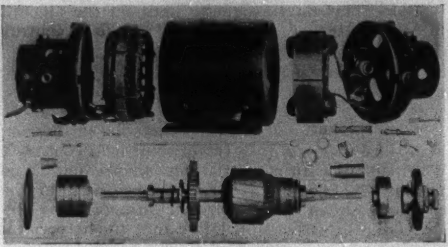


Fig. 7. Component parts of the 1,000-cycle set shown diagrammatically in Fig. 5

Fig. 11 illustrates an improved up-to-date design of rotor and stator structure for producing a 500/20-cycle signal. In this case, there are 11 teeth and 12 slots equivalent to 12 rotor tooth pitches (as the beginning of the smooth portion is equivalent to another tooth), but located on less than half the rotor circumference. In this case, the circumferential pitch of the rotor teeth $= \frac{\text{Circumference}}{25^1/_2} = \frac{3.64 \text{ in.} \times \pi}{25^1/_2} = 0.449$ in. Peripheral velocity at

$19.6 \text{ rps} = 3.64 \text{ in.} \times \pi \times 19.6 = 224.5$ in. per sec, $\frac{224.5}{0.449} = 500$ cycles per sec: rotor diameter being 3.64 in. This method of calculating frequency fundamentally is more correct than the usual formula $f = PS$, which assumes a full number of equally spaced teeth. Another advantage of using a partly toothed rotor is that there is no single step limitation to the tone frequency. For example, with a full number of teeth, either 25 or 26 teeth would have to be used, but with a partly toothed rotor the exact tone frequency of 500 cycles, at 19.6 rps, corresponding to $25^1/_2$ teeth, is just as easy to obtain as some other frequency corresponding to an integral number of teeth for the entire circumference.

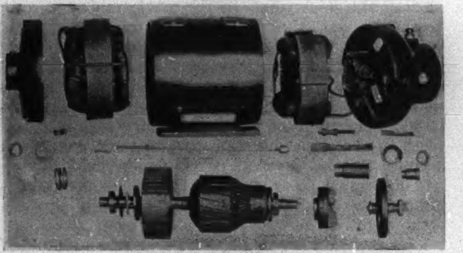


Fig. 8. An inductor alternator set for generating 1,000/20-cycle tone directly—no mechanical interrupters

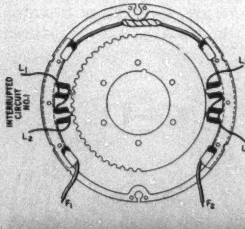


Fig. 9. Cross section of stator and rotor assembly, showing arrangement of teeth and windings of inductor alternator for generating 1,000/20-cycle tone directly

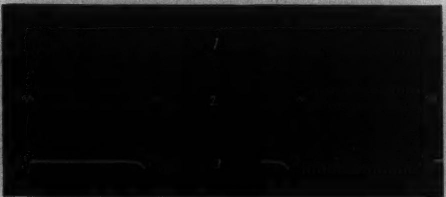


Fig. 10. Oscillogram of interrupted output generated by the special machine shown in Figs. 8 and 9. Also oscillograms of the 2 interrupted circuits of this generator connected series cumulative and series opposed

1. Cumulative connection 2. Opposed connection 3. One interrupted circuit

The detail of particular interest to be noted in Fig. 11, however, is the fact that the stator teeth have been converged so as to be spaced only $^1/_2$ rotor tooth pitch apart. The effect of this is to interrupt the tone sharply, and to prevent the shading and interference so evident in the oscillograms of Fig. 10. An oscillogram of the interrupted output of this up-to-date 500/20-cycle generator is shown in Fig. 12.

THE GENERATION OF MODULATED SIGNALING CURRENTS

Tone Alternator. For many years a large percentage of telephone ringing machines have been fitted with so-called "high speed interrupters" for the generation of special tones. This high speed interrupter is a cylindrical drum containing several interrupter rings which are fitted with alternate live and dead segments contacting with brushes located in such a way as to interrupt battery current at a rate that will produce the desired tones. Each interrupter ring unit of this interrupter produces a different kind of a tone for a special signaling purpose. The interrupter drum is mounted directly on a shaft extension of the ringing machine and operates at a speed of about 1,150 rpm. The tones produced are satisfactory, but the cost of maintaining the brushes and rings is high.

Following the successful generation of the interrupted tone signal, and the elimination of the mechanical interrupters from the voice frequency signaling set it was thought that a similar result might be possible in connection with the high speed interrupter.

This high speed interrupter produced 3 tones—high tone (411 cycles), low tone (137 cycles), and the audible ringing signal, which was a very special tone having a continuous frequency of 411 cycles—

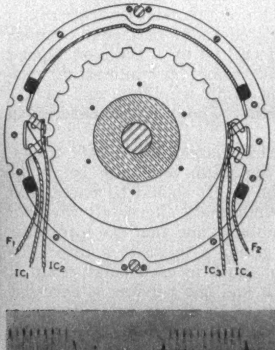


Fig. 11. A stator and rotor assembly, showing arrangement of teeth and windings of an improved type of inductor alternator for the generation of interrupted output

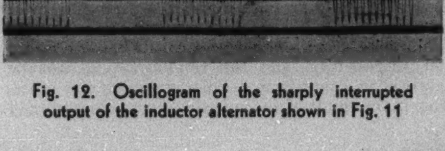


Fig. 12. Oscillogram of the sharply interrupted output of the inductor alternator shown in Fig. 11

the same as the high tone—but interrupted at a lower frequency rate so as to sound like a ringing signal. It was suggested by the telephone engineers that this tone could be duplicated by a sine wave of 411 cycles fundamental frequency varied in voltage in a 1 to 4 ratio at a 40-cycle rate. A method of generating such a modulated tone by inductor alternator was conceived and successfully accomplished in the first model. It was found, however, that the pure 137-cycle tone of the first model was not a satisfactory low tone as the wave, being nearly sinusoidal, lacked the quality of the mechanically interrupted tone to which the operators had become accustomed. It was thought necessary, therefore, to generate a low tone that would sound more like the mechanically interrupted tone. After considerable study the telephone engineers in charge of this investigation decided that a correct tone would be obtained if 660 cycles could be generated by an inductor alternator in such a way as to be varied in voltage or amplitude in a 1 to 4 ratio at a 120-cycle rate. At the same time the output requirements of this so-called tone alternator were increased several hundred per cent, the audible ringing tone was specified as 420 cycles modulated in a 1 to 4 voltage ratio at a 40-cycle rate, and the high tone raised to 500 cycles. The design of this final tone alternator consisting of 2 modulated and 1 pure tone channel, built into 1 unit and excited by a common bipolar field system brings out some very interesting relations of the a-c generating windings, and of the stator and rotor teeth. These are considered in detail as follows:

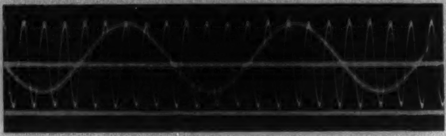


Fig. 13. Oscillogram of "high tone" with 60-cycle timing wave

The High Tone. This channel is a simple design, the cross section of the stator and rotor being the same as shown in Fig. 1. It should be noted that the coils of the a-c winding are alternately reversed polarity all the way around, and that the top stator tooth in each polar group is opposite a rotor slot while the lower stator tooth in each polar group is opposite a rotor tooth and the winding is reversed in going from the top tooth of one polar group to the top tooth of the other polar group, because the polarity of the main field also reverses at this point. If the rotor had an even number of teeth, however, such as 24 or 26 instead of 25, the top stator teeth of the 2 polar groups would be opposite a tooth and a slot, respectively, and the winding would not be reversed in going from 1 polar group to the other. This is the result of the rule that an even number of stator teeth must be used in each polar group, spaced a multiple of $^1/_2$ rotor tooth pitch apart. An even number of stator teeth, such as N, covers a polar angle equal to $N-1$ stator tooth pitches. The rotor teeth covered by 1 polar group of stator teeth, therefore, are equal to $(N-1)^1/_2K$ in which K is an odd number (1, 3, 5 etc.—that is, $^1/_2$, $^3/_2$, or $^5/_2$ rotor tooth pitches). The rotor teeth covered by both polar groups $= 2(N-1)^1/_2K = (N-1)K$. Since $(N-1)$ and K are both odd, neither contains a factor 2, and the expression $(N-1)K$ always is odd, but integral, regardless of the total number of rotor teeth. If the total number of rotor teeth is odd the difference between this number and $(N-1)K$ must be even. Hence half this difference (in each interpolar space) is integral bringing adjacent top teeth of the 2 polar groups over rotor teeth or rotor slots at the same time. If the total number of rotor teeth is even, the difference between this total number and $(N-1)K$ will be odd. Half of this odd number difference, therefore, will be fractional putting adjacent stator teeth of the 2 polar groups over a slot and a tooth, respectively. This makes it necessary to place the a-c windings around these teeth in the same direction to add their voltage on account of the reversal of the main field flux in passing from 1 polar group to the other. An oscillogram of the "high tone" with a 60-cycle timing wave is shown in Fig. 13.

The Audible Ringing Signal. This is a modulated tone, being 420 cycles modulated by a 1 to 4 voltage variation at a 40-cycle rate. Its oscillogram is shown in Fig. 15 with a 60-cycle timing wave. Referring to the cross section shown in Fig. 14 of the stator and rotor punchings for this special inductor, it will be observed that there are 4 groups of 2 stator teeth each, spaced 90 deg apart. Two of these

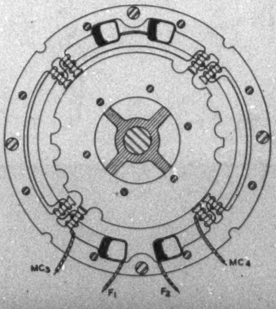


Fig. 14. A stator and rotor assembly, showing arrangement of teeth and windings of audible ringing tone channel of tone alternator

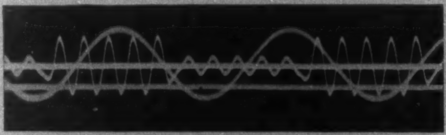


Fig. 15. Oscillogram of audible ringing tone with 60-cycle timing wave

groups come under each field pole. The rotor has 2 opposite toothed portions and 2 opposite smooth portions. The circumferential pitch of the rotor teeth is such that 420 cycles will be generated in any stator tooth winding while the toothed portion of the rotor is passing, if the rotor is revolved at 1,200 rpm (20 rps): $\frac{420}{20} = 21$, that is, if the rotor were completely filled with teeth of this same pitch, it would have 21 teeth. Each generating group of teeth contains 5 rotor slots and teeth exactly, but these are spaced diametrically opposite so that each smooth portion covers an angular space equal to $5^1/_2$ rotor tooth pitches.

In order to secure the modulated wave, the opposite stator tooth, groups 3 are wound with 4 times as many turns per coil as the other opposite groups marked 2. All of the stator windings, however, are connected in series. With this arrangement, as the rotor revolves, the toothed portions generate alternately on windings 2 and 3 producing voltage in a 1 to 4 ratio—because of the ratio of turns, and at a 40-cycle rate because there are 2 groups of teeth on the rotor turning at a speed of 20 rps.

The Low Tone. This is a very special modulated tone particularly difficult to generate because the rate of modulation is so high, being equal in frequency to 18.2 per cent of the fundamental tone. This tone is 660 cycles modulated at a 120-cycle rate. In the cross section shown in Fig. 16 there are 6 groups of 2 converging stator teeth each, and 4 single stator teeth. The single stator teeth are spaced 60 deg apart, plus half a rotor tooth pitch, while the groups of converging teeth are spaced 60 deg apart. The rotor tooth pitch is such as to generate 660 cycles, while the toothed portions are passing under stator teeth. If the same winding were placed on all the stator teeth, the 4 single teeth would generate one-third the voltage of the 12 converging teeth. The winding on the single teeth is reduced sufficiently, however, to make the voltage ratio 4 to 1 as specified. As the rotor revolves at 1,200 rpm, generation of 660 cycles occurs alternately in the 6 groups of converging teeth and in the group of 4 single teeth producing the wave train shown in Fig. 17.

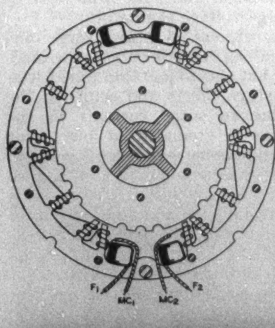


Fig. 16. Cross section of stator and rotor assembly, showing arrangement of teeth and windings of "low tone" channel of tone alternator

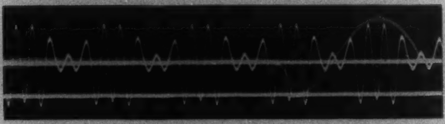


Fig. 17. Oscillogram of "low tone" with part of a 60-cycle timing wave

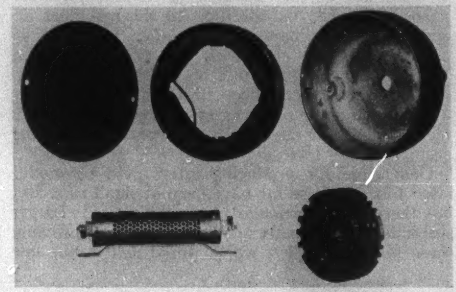


Fig. 18. A tone alternator shown disassembled

A view of the tone alternator disassembled is shown in Fig. 18. The 3 sets of rotor laminations for the 3 channels are mounted on a brass spider and riveted together, brass spacers being used between the steel punchings to prevent frequency interference. The 3 stators also are shown assembled in a single unit with the windings in place; a common set of field coils is used to excite the stators. The laminated stator structure then is assembled in the aluminum case shown at the right. The rotor is placed on the shaft extension of the ringing machine replacing the high speed mechanical interrupter, while the aluminum case containing the stator is rabbeted to the end of the ringing machine bearing bracket. This generator should require no maintenance whatever as it has not even added a bearing to the ringing machine assembly.

The pins shown on the end of the rotor are used for driving a coupling connected to a gear reduction which in turn drives the so-called low speed interrupters that are a part of many of the ringing machine units. The perforated cage encloses a resistance tube for connection in the field circuit of the tone alternator. This tube is adjusted on test so as to bring the no load and full load voltages of the high tone, low tone, and audible ringing channels within certain specified limits.

The output ratings of these 3 channels are as follows:

Low tone	1.0 volt,	4.0 amp
High tone	1.5 volts,	4.5 amp
Audible ringing tone	0.6 volt,	1.0 amp

Thermocouple instruments are used for measuring the output of these special machines. In some cases, voltmeter and ammeter are both used, but more often a noninductive resistance carefully measured is connected across the output leads, a voltmeter then being the only instrument required.

CONCLUSION

It is difficult to predict just what course the future development of this special type of inductor alternator will take. In addition to the machines described in this paper many other combinations and arrangements, of course, are possible utilizing the fundamental principles of supplying only part of the rotor circumference with teeth and in winding different numbers of turns around groups of stator teeth periodically affected by the separate generating groups of rotor teeth.

Generators for producing interrupted or modulated tones built so far have been of small capacity, but there is no particular power limitation. Larger size inductor alternators could be designed, utilizing these same principles, which would deliver the low tone or any of the other tones in kilowatts instead of watts, if there were a demand for such greater power.

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Heavy Surge Currents—

Generation and Measurement

There has been developed a generator for the production of heavy surge currents in excess of 100,000 amperes and of effective durations greater than 100 μsec. Methods of measuring these currents by the cathode ray oscillograph with good engineering accuracy also have been developed. Some features of lightning phenomena may now be investigated which were not possible of study with the high-surge-voltage generator.

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FIELD investigations and experience have indicated that surge currents are important features of lightning phenomena, in some respects even more important than surge voltages. This consideration has led to the development of the heavy-surge-current generator which is described in this paper.

A prerequisite for the production of heavy surge currents is a surge-generator discharge circuit of low impedance; the maximum current discharged from such a circuit is inherently oscillatory. To secure an aperiodic wave, series resistance is inserted in the discharge circuit; this results however in a lowering of the maximum current output. Since the current generated bears a linear relation to both the charging volts and the capacitor voltage, it can be controlled in much the same way as the voltage of the surge voltage generator.

The accurate measurement of heavy surge current is beset by difficulties due not only to the magnitude of the current but also to its rapid time variation. To eliminate stray effects and errors in the measuring circuit due to surge currents in the ground, the generator is grounded at one point only—in this way suppressing currents flowing in the ground. At this grounded point a resistance shunt is inserted in the generator circuit. This shunt must be practically noninductive and must have a constant resistance independent of temperature and frequency effects. The voltage across the shunt is transmitted through a short segment of cable for measurement at the cathode ray oscillograph.

With the development of the heavy-surge-current generator and of the technique of heavy-surge-current measurement, surge currents in excess of 100,000 amp and of effective duration greater than 100 μsec have been produced. These currents have been measured with good engineering accuracy.

The physical characteristics of heavy surge currents produced in the laboratory are comparable in effect to those produced in the field by direct or near-direct lightning discharges, for example: the ex-

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Full text of a paper recommended for publication by the A.I.E.E. committee on instruments and measurements, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 23–26, 1934. Manuscript submitted Oct. 20, 1933; released for publication Nov. 21, 1933. *Not published in pamphlet form.*

plosive and destructive effects, the fusing of conductors, the sound and light produced, and other physical manifestations. One of the practical applications of the heavy-surge-current generator has been in connection with the testing and development of the deion gap for surge-proof distribution transformers.

IMPORTANCE OF HEAVY SURGE CURRENTS

The early studies of the protection of high voltage lines against lightning strokes, which indicated that current was as important a characteristic of lightning phenomena as voltage, also showed that this was true particularly in its bearing on the design of ground wires and tower footing resistances where current discharges are involved.[1] Later, considerable attention was given to the protection of low voltage circuits against lightning[2] and growing out of this study a special form of protected distribution transformer[3] was developed. Following the installation of several thousands of these transformers, many of them in regions highly exposed to lightning, valuable field experience emphasizing the importance of lightning current in distribution circuits has been obtained. Among other things, these field data establish the fact that while heavy-lightning-current discharges occurring directly at or near the transformer are rare, yet they take place more often than was originally suspected on the strength of previous available experience.

SURGE CURRENTS OBTAINABLE FROM HIGH-SURGE-VOLTAGE GENERATOR

At the time of the investigation of surge voltages,[4] studies were made of the currents obtainable from the 3,000,000-volt surge-voltage generator at Sharon, Pa., and subsequently laboratory tests were made. The results of these tests are summarized below, for they have served as a useful guide in the development of the heavy-surge-current generator design and operating technique.

Fig. 1. Surge current waves produced by a 3,000,000-volt surge-voltage generator

Briefly: The maximum current obtainable with the voltage generator short-circuited and all inserted resistance removed is of the order of 20,000 amp. This current (Fig. 1*A*) is oscillatory, having a period of 5 μsec and a duration to half-crest value of 10 μsec. With 600 ohms inserted in the generator, an exponential discharge (Fig. 1*B*) of duration 4 to 5 μsec is obtainable with a crest-value of about 3,000 amp. These current waves are generally characterized by an ill-defined front having superposed thereon high-frequency oscillations which are due to the effects of ground and to the short-circuiting lead from the high voltage terminal to ground.

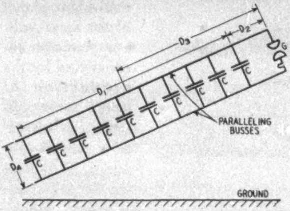

Fig. 2. Circuit diagram of one stair of the surge voltage generator with all capacitor groups reconnected in parallel

With an inductance of 100 to 200 μh inserted in the generator circuit, the initial rate of current discharge is decreased and for both the oscillatory and exponential waves, the oscillograms (Figs. 1*C* and *D*) therefore become well-defined on the front, but the maximum current generated is reduced materially.

These preliminary investigations on the generation and measurement of surge currents definitely pointed out that as a prerequisite for the production of heavy surge currents it is essential that the surge-current generator circuit be of much lower impedance than prevails with the surge-voltage generator. They also suggested the desirability of eliminating the ground as part of the discharge circuit by confining the surge current to a definite path and emphasized the necessity in current measurement technique of the use of noninductive, constant-resistance shunts free from appreciable skin effect and unaffected by temperature.

ADAPTATION OF THE 3,000,000-VOLT SURGE-VOLTAGE GENERATOR FOR HEAVY SURGE CURRENTS

In the early work on heavy surge currents it was found from analysis that by paralleling the 30 capacitor groups of the surge-voltage generator[5] and discharging them at the junction of the first and second stairs (see Fig. 6), it would be possible to produce currents of the order of 75,000 amp and of a fundamental period of 30 μsec and more. Simply stated, this analysis is as follows.

The equivalent circuit of the first stair of capacitors (10 groups) is represented in Fig. 2. The average distance of the 10 capacitances C from the discharge gap G is D_3. The 2 paralleling busses of effective radius r are set D_4 distance apart. The effective lumped inductance considered in series with the total capacitance $C_0 = 2.4$ μf is approximately

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[1] For all numbered references see list at end of paper.

$$L_a = 0.28\left(\log_{10}\frac{D_4}{r}\right)D_3 + 0.28\left(\log_{10}\frac{D_3}{r}\right)D_4 \ \mu\text{h}$$

where the linear dimensions are in feet. On the basis of these simplifications the lumped circuit constants of the 3 stairs of capacitors are given in Fig. 3. The first and second stairs of capacitors are symmetrically disposed with respect to the discharge gap and therefore each of these contributes the same amount of current, calculated as follows:

$$\text{Oscillation impedance} = \sqrt{\frac{L_a}{C_0}} = 2 \text{ ohms}$$

$$\text{Period of oscillation, } T = 2\pi\sqrt{L_aC_0} = 31\ \mu\text{sec}$$

The effective series resistance of the leads, busses, etc., taking into account skin effect[6] at 30 kc but neglecting other possible losses in the capacitors, at the discharge gap, etc., is $r_1 = 0.1$ ohm. On this basis the fundamental oscillation would dampen from crest to half value in approximately $\dfrac{2\ L_a}{Tr_1} =$ 4 oscillations. Then for a capacitor voltage $E =$ 75,000 volts, the combined currents discharged at the gap from the first and second stairs of capacitors would be 70,000 amp. The third stair of capacitors is located well above the discharge gap, connecting thereto through a cable extension of 12-μh inductance. Accordingly, the third stair contributes a current of only about 20,000 amp and of 45 μsec period.

It was found that altogether a total current of approximately 75,000 amp at a period somewhat greater than 30 μsec could be produced. Therefore, a scheme of paralleling busses was devised so that the surge-voltage generator could be utilized to produce heavy surge currents. The calibration curves of current in Fig. 4 and the corresponding oscillograms in Fig. 5 show that the experimental data obtained are in substantial agreement with the analysis based upon the simplifying assumptions stated above. In Appendix I the circuit characteristics of surge current generators are treated more fully and in detail.

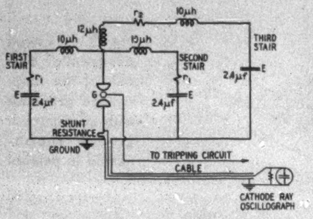


Fig. 3. Simplified equivalent circuit of the surge voltage generator reconnected for the production of heavy surge currents. Measurement circuit also shown

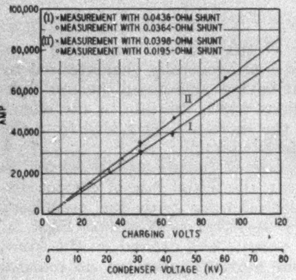


Fig. 4. Current output of surge voltage generator reconnected for the generation of current. The 30 capacitor groups are all connected in parallel

I. Paralleling strap conductors mounted on charging bus supports

II. Paralleling bus bars mounted on terminals of capacitors

Fig. 5. Oscillograms of surge currents produced with surge voltage generator reconnected for the generation of current

Fig. 6. Laboratory view of surge voltage generator reconnected for current and of the adjunct current generator. Note the triple gap on platform

The operation of the surge-current generator is much the same as in surge-voltage technique.[7,8] The measurement of the currents are conducted as follows: Referring to Fig. 3, the generator circuit is connected to ground at one point only to eliminate current flowing therein; furthermore, the shunt is inserted in the circuit at the grounded point and the voltage drop v_s across the shunt is transmitted to and measured at the voltage plates of the cathode ray oscillograph. Then from the resistance of the shunt R_s the current measured is $i_s = v_s/R_s$. With this arrangement of the surge current generator, the current measured at the oscillograph was found to be practically independent of effects due to ground; this is shown in the oscillogram of Fig. 5*A*.

In Table I are summarized pertinent data on the first group of shunts that were used to measure surge currents as large as 75,000 amp. It was found that in comparing any 2 or more shunts, the same connections for the busses, leads, discharge gap, etc., had to be used since any changes in them would alter the circuit inductance sufficiently to affect the current generated for a given charging voltage. For example, the calibration curves I and II in Fig. 4 show appreciable differences in the currents, these being due to alterations that had been made in the set-up of the busses. The 2 shunts compared with each other in curves I and II, respectively, while somewhat different from each other, both measure practically the same current. The characteristics of shunts for heavy surge current measurements are discussed in greater detail further on and also in Appendix II.

To render the wave form of the surge current aperiodic, or at least to simulate the aperiodic wave form, resistance is inserted in the current generator. In so doing the amplitude of the current is reduced. The characteristics of the current generated are given in the oscillograms of Fig. 7 and the relation between maximum current and inserted resistance are plotted in Fig. 8. It is of interest to note that the maximum current is independent of the arrangement of the resistors with respect to the discharge gap.

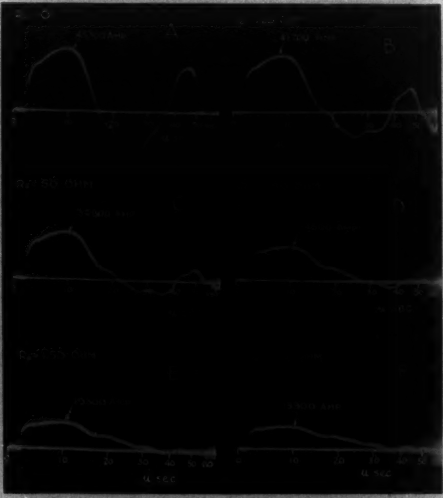


Fig. 7. Oscillograms of surge current with resistance (R_0) inserted in generator

DESIGN AND CHARACTERISTICS OF THE ADJUNCT SURGE-CURRENT GENERATOR

The purpose in providing an adjunct current generator for use in conjunction with the parallel-operated surge-voltage generator already available was to produce surge currents of the order of 100,000 amp or more. To accomplish this, the adjunct current generator had to be designed to have the proper natural period and other electrical constants, to permit operating it successfully in parallel with the reconnected surge voltage generator. As shown in Fig. 6, the adjunct generator consists of 8 groups of 4 capacitors paralleled by 2 busses.

Fig. 8. Current output as affected by resistance inserted in generator. The 30 condenser groups are connected in parallel. Load resistance is at the discharge gap

Current output is given in per cent of maximum current for load resistance, $R_0 = 0$

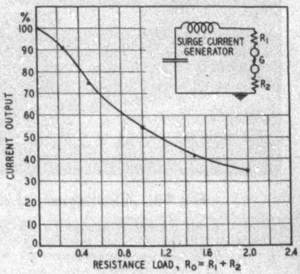
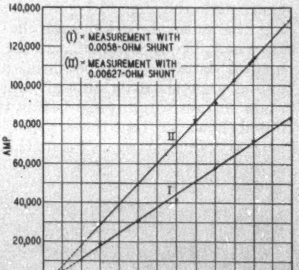


Fig. 9. Current output of surge current generator

I. Current output of adjunct surge current generator

II. Current output of surge current generator proper and adjunct surge current generator both connected in parallel



The total capacitance of the adjunct is $C_0 = 7.7$ μf. The equivalent series lumped inductance, calculated by the simplified method described previously, is $L_a = 4.3$ μh. Accordingly the characteristics of the circuit for a capacitor voltage of 75,000 volts are as follows: Oscillation impedance = 0.75 ohms; period of fundamental oscillation = $2\pi\sqrt{L_aC_0} = 36$ μsec; maximum current of fundamental oscillation = 75,000 divided by 0.75 = 100,000 amp. This calculated value of the maximum current generated by the adjunct does not take into account attenuation or the fact, as shown subsequently in Appendix I, that harmonic oscillations are superposed on the fundamental, both factors reducing the actual maximum current to a value somewhat below that calculated above.

Curve I of Fig. 9 gives the relation between the charging volts and the crest value of the current generated, and Fig. 10A gives the oscillograms showing the natural period and the wave form of the current. From these it can be seen that experimental data are in substantial agreement with the above analysis even though this analysis is based upon certain simplifying assumptions. It should be noted, however, that the first loop of the oscillograms is of rectangular wave form, this being due to harmonic oscillations superposed upon the fundamental, as discussed at length in Appendix I.

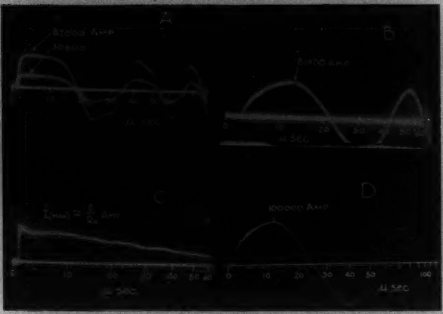


Fig. 10. Oscillograms of surge current

A. Surge current produced by the adjunct surge current generator
B, C, and D. Surge current for various conditions of load at discharge gap (2 generators in parallel)

Reconnected Surge Voltage Generator and Adjunct Current Generator in Parallel

To produce surge currents above 100,000 amp, the 2 generators mentioned above are operated in parallel. The laboratory arrangement and also the triple discharge gap located on the platform are shown in Fig. 6. The total capacitance of the 2 generators in parallel is 14.9 μf. The relation of the current output to the charging voltage is plotted in Curve II of Fig. 9. Oscillogram B of Fig. 10 gives the wave form and the period of the surge current. It should be noted that since the natural period of each of the 2 generators individually is between 35 to 40 μsec, the period for the 2 in parallel remains practically unchanged. However, the surge current output from the 2 generators in parallel is not the sum of the currents from each separately, but rather a value somewhat less; the reason for this is as follows: The discharge circuit comprising the discharge gap and common to both generators has an appreciable inductance relative to the total circuit inductance. Furthermore, this common inductance, being well lumped and in series with the rest of the circuit, results in a wave form of current as shown in the oscillogram of Fig. 10B, which can be seen to be substantially more sinusoidal than for the case when either of the 2 generators operates alone.

The other 2 oscillograms in Fig. 10 are worthy of study. When increasing the load resistance to approximately 3 ohms, the current output becomes practically equal to the voltage divided by the load resistance, and the wave form is then substantially exponential, rising abruptly to crest and receding to half crest value in nearly 40 μsec, as shown in oscillogram C. With zero resistance load and the length of the discharge path common to the 2 generators increased, the period of oscillation is increased as shown in oscillogram D and the output for a given charging voltage is somewhat decreased, due to the obvious fact that the total series inductance of the discharge circuit is increased thereby.

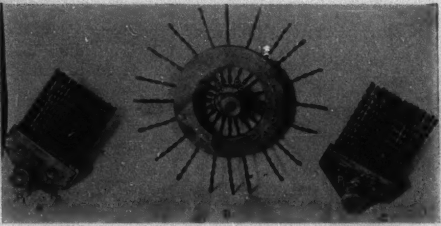


Fig. 11. Resistance shunts for the measurement of heavy surge currents

Shunts for the Measurement of Heavy Surge Currents

As can be seen from Fig. 3, the technique of heavy surge-current measurement consists essentially of recording the voltage drop across a resistance shunt at the voltage plates of the cathode ray oscillograph. Since the voltage that can be measured at the oscillograph is of the order of 1,000 volts, the product of the crest current and of the shunt resistance must be of this order.

The requirements of a resistance shunt, intended to measure heavy surge currents with good engineering accuracy, are best understood by references to specific examples of shunt performance. The shunt must be practically noninductive. It must have a constant resistance independent of temperature and its conductor elements should be practically free from skin and proximity effects[6] within the range of frequencies measured. Furthermore it should carry the current without excessive heating.

Conductors of No. 20 A.W.G. manganin wire, for example, twisted together noninductively as shown in Fig. 11, were found to satisfy the above requirements in a good measure. The maximum surge-current carrying capacity of No. 20 manganin wire for the oscillatory waves (Fig. 5) is in the order of 10,000 amp, so that the shunts with 20 elements in parallel, shown in Fig. 11, can carry 200,000 amp satisfactorily. Shunts, described in Table I, were subjected to heavy surge currents up to the fusing point of the conductors; even then their resistance was found to remain substantially constant, as was the case, for example, with the shunts in Fig. 4. These shunts, although differing in construction, recorded practically the same current values.

A strictly noninductive shunt is difficult to realize. However, the inductive drop can be reduced practically to a small amount relative to the ohmic drop by a disposition of conductor elements as shown in Fig. 11. For shunt resistances of the order of milliohms, the inherent inductance permissible should be limited to a value of the order of millimicrohenries, in order that the shunt may record surge currents of the time-characteristics under consideration within a few per cent deviation from true value.

No less important in the construction of the shunt is the proper location of its potential terminals. It is essential that the leads from the core and sheath of the cable shall be as short as possible and that they connect directly to the terminals without open loops, since loops would inevitably entail mutual couplings with the discharge circuit and thus result in errors of measurement. The method of inserting the shunt in the discharge circuit is also important; for example, it will be noted in Fig. 11 that the current is made to enter at right angles to the plane of the shunt elements. Furthermore, if various shunts are to be compared with each other, for performance, the effective inductance of the generator discharge circuit must not be altered appreciably with the insertion of any one of the various shunts being compared since the comparison should be made on the basis of equal charging voltage applied to the current generator.

Shunt *B*, Fig. 11, was found, both theoretically and experimentally, to conform with the cited requirements for a shunt good for very heavy surge-current measurement. Curve II in Fig. 12 is the current calibration of the generator with shunt *B* (0.00627 ohm). Shunt *A* measured values for current which were higher by a small percentage, as indicated in curve III. Curve I corresponds to a higher resistance shunt (0.0195 ohm) which had already been found in good agreement with other shunts of still higher resistance.

Oscillograms *A* and *B* in Fig. 13 were recorded with the 0.00627-ohm shunt (shunt *B*) and the 0.0195 shunt (Table I), respectively. These 2 oscillograms are practically identical in period, damping, and wave form. Oscillogram *C* was taken with shunt *A* (0.00579-ohm). This shunt has potential terminals at the ends of the copper plates. Shunt *C* is similar to *A* except that the 2 potential terminals are located on opposite copper plates, thus entailing a loop of the cable terminals in connecting. Oscillogram *D* was recorded with shunt *C;* it shows an even higher overshoot than oscillogram *C*, and accordingly a still higher measurement of current than with shunt *A*.

RÉSUMÉ OF INVESTIGATIONS OF DISCHARGES AND THEIR PHYSICAL CHARACTERISTICS

Extensive tests have been made with heavy surge currents and there are good reasons indicating that these currents are fairly representative of the heavy surge currents that are found in the field. This statement does not preclude the possibility of even more intense and still more rare, direct-stroke lightning-current discharges. These are the reasons.

First: The very heavy surge currents produced in the laboratory readily explode a No. 14 copper wire.

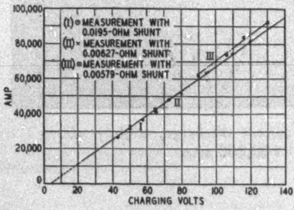


Fig. 12. Comparison of current measurements made with different shunts. The 30 capacitor groups are connected in parallel

Table I—Data on Shunts

Shunt Resistance[1] —Ohms	Current Measured per Inch Deflection on Film —Amperes	Description of Shunt[2]	Max. Current-Carrying Capacity[3] —Amperes
0.0436	19,500	Six elements of No. 20 manganin wire in parallel, each element 12 in. long	65,000
0.0364	23,400	One element of No. 12 manganin wire 5 in. long	Greater than 40,000
0.0398	21,400	Three elements of No. 20 manganin wire in parallel, 7 in. long	33,000
0.0195	43,600	Six elements of No. 20 manganin wire in parallel, 7 in. long	65,000

1. D-c resistance measured with the Kelvin bridge. Skin and proximity effects at 30 kc for manganin conductors here considered increase d-c resistance inappreciably

2. Each element of wire is extended to half-length and twisted back onto itself noninductively

3. Current that produced excessive heating of conductor and diffusive burning of insulation. Wave form of current as in oscillograms of Fig. 5

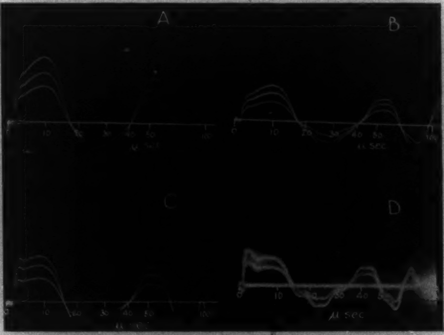


Fig. 13. Oscillograms of surge currents taken with different shunts to illustrate their performance

In this connection, a simple experiment conducted by Prof. E. C. Starr of Oregon State College is illuminating. He erected a lightning rod on the top of a mountain peak and connected it to conductors laid along the sides of the peak. In this path, which completed the lightning discharge to earth, he inserted sections of different-sized copper wires connected in series, making it possible to determine the fusing effects of the very heavy currents in a direct stroke. The conclusions from this experiment and from similar observations of the kind are that the current in a direct lightning-stroke can be expected to fuse copper wires of No. 14 and smaller, but that larger conductors will ordinarily conduct the current successfully to ground. Similar data have been obtained by the author with a lightning stroke at Sharon, Pa., where No. 10 copper wire of a radio antenna was beaded at the point of contact with the stroke, but not fused. Observations by other investigators are in substantial agreement with these findings.[9,10,11]

The following relationship of the current for a single lightning discharge that would produce fusing of a copper conductor is of great interest, since it makes possible an estimate of the current in a lightning stroke from observations on the fusing of conductors:

$$I_{(max)} = 320{,}000\,\frac{A}{\sqrt{T}}$$

The formula is deduced directly from the curves of Fig. 14, which were determined experimentally in the laboratory. (On account of skin effect, the effective area A used should be somewhat less than its physical value for $T = 20$ to 60 μsec and for large size solid conductors of 1.3 mm diameter and greater.) The symbols are defined in Appendix III, where the expression is arrived at with good approximation from theoretical considerations.[12] Similar expressions have been obtained for other wave forms of current and for conductors of other materials, the constant being a function of the wave form and of the material. The expression for fuse links as ordinarily used in distribution systems is in substantial agreement with the data published by other investigators.[13]

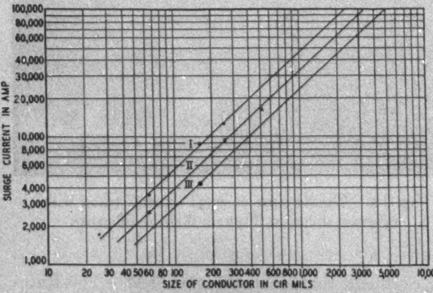


Fig. 14. Fusion characteristics of copper conductors with surge currents

I. Steep front 9-μsec surge (exponential tail)
II. Steep front 18-μsec surge (exponential tail)
III. Steep front 40-μsec surge (exponential tail)

Second: Field experience has revealed valuable information on direct or near-direct strokes of lightning at distribution transformers provided with deion gap protection. The plugs or electrodes of the deion gaps discharging these heavy surge currents were marked on their faces with a "klydonograph" figure or record. These figures when compared with similar figures obtained on deion gaps tested with known heavy surge currents in the laboratory showed marked similarities in all respects, indicating that the currents in the laboratory were closely comparable to those that have occurred in the field.

Third: It is well known that in cases of a direct or near-direct strokes of lightning at distribution transformer installations, fuse cutouts and similar apparatus have been completely destroyed and shattered.

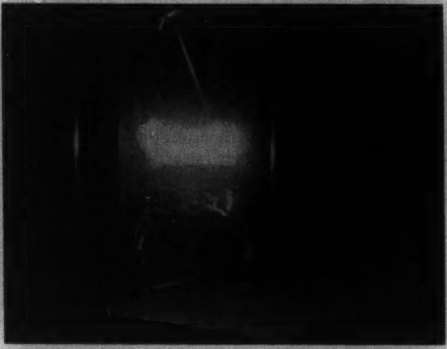


Fig. 15. Surge current discharge, slightly above 100,000 amp

Similar effects have been produced in the laboratory with heavy surge current tests and with heavy surge current tests combined with power excitation.

The light produced by these heavy surge-current discharges is intense in brilliancy and blinding, much the same as when looking directly at the sun. The sound produced by the arc discharge, although the arc is only several feet long, is uncomfortable and even painful to the ear. The diameter of the incandescent part of the arc is of the order of one foot and more. In Fig. 15 is illustrated a heavy surge-current discharge of 100,000 amp.

Appendix I

The circuit of the surge current generator of Fig. 2 is represented in Fig. 16*A* as an ideal network with distributed constants. Neglecting for the moment the effect of resistance and other losses, traveling waves of voltage and current are then set up as given in Fig. 16*B*. The voltage and current at any point n are plotted in Fig. 17*A* and *B* as functions of time t. The equations of current

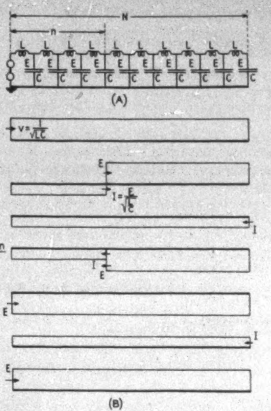


Fig. 16. Surge current generator with distributed constants

A. Circuit of surge current generator having distributed constants

B. Traveling waves of current and voltage in the distributed circuit

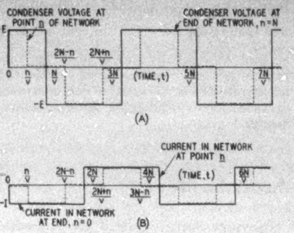


Fig. 17. Voltage and current as functions of time for the distributed circuit of Fig. 16*A*

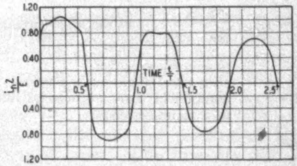


Fig. 18. Damping of current at the discharge gap for the distributed circuit of Fig. 16*A*

and voltage as a function of time then can be arrived at conveniently from the Fourier integral theorem. Expressed in their final solution, they are as follows:

$$i_n = -\frac{4}{\pi}\frac{E}{Z}\sum_{k=1}^{k=\infty}\frac{1}{k}\cos\left(\frac{k\pi n}{2N}\right)\sin\left(\frac{2\pi kt}{T}\right) \tag{1}$$

and

$$e_n = \frac{4}{\pi}E\sum_{k=1}^{k=\infty}\frac{1}{k}\sin\left(\frac{k\pi n}{2N}\right)\cos\left(\frac{2\pi kt}{T}\right) \tag{2}$$

where $k = 1, 3, 5,$ etc.

$L_0 = NL$ and $C_0 = NC$

Fundamental period, $T = \frac{4N}{v} = 4\sqrt{L_0C_0}$ since $v = \frac{1}{\sqrt{LC}}$

Surge impedance, $Z = \sqrt{\frac{L}{C}} = \sqrt{\frac{L_0}{C_0}}$

It can be demonstrated readily that eqs 1 and 2 satisfy the general differential equations:

$$\frac{\partial e_n}{\partial n} = -L\frac{\partial i_n}{\partial t};\quad \text{and}\quad \frac{\partial i_n}{\partial n} = -C\frac{\partial e_n}{\partial t}$$

Next, considering the dissipative characteristics of the distributed circuit in Fig. 16*A*, with particular reference to the current at the discharge gap, and denoting the total distributed resistance as r_0, then in accordance with the classical theory[14,15] the waves in Fig. 17*B* would decay at substantially an exponential rate, i. e.,

$$\epsilon^{-\frac{r_0}{2L_0}t}$$

But the resistance of large-section copper conductors, as well as losses in the dielectric of the capacitors, are both functions of the frequency of oscillation. As an illustrative example, let it be assumed that the effective resistance increases in direct proportion with the frequency, then the fundamental and harmonic oscillations in eq 1 would dampen from crest to half-crest value in the same number of oscillations. Considering the case where the amplitude of the oscillations dampen to half-crest value in 3 oscillations, then introducing damping factors in eq 1 and dropping the negative sign for convenience, the current discharged at the gap is plotted in the curve of Fig. 18. This curve clearly indicates that on account of the rapid damping of the higher-frequency oscillations, the current assumes practically a sinusoidal wave form after a few oscillations. On the basis of still greater damping with frequency than stated above, the current would assume still more rapidly practically a sinusoidal form. To be sure, the exact determination of the damping factors at high frequencies involves many complications; however, a close determination of these factors is not of vital importance here and therefore further detailed analysis is considered to be beyond the scope of the present work.

In practice, the capacitor bank connects to the discharge gap through leads of appreciable length, shown as D_2 in Fig. 2, thus introducing at the discharge gap in Fig. 16*A* an appreciable lumped inductance relative to the total distributed inductance L_0. Furthermore, the capacitor groups C are not uniformly distributed but lumped into a finite number of groups. In addition, each group of capacitors connects to the 2 paralleling busses through leads which are short but which nevertheless entail some inductance and resistance in series with each C. Considering these modifications introduced in the ideal distributed network in Fig. 16*A*, the combined effect is to round off the otherwise rectangular shape even of the first loop of the current as can readily be seen from the oscillograms shown. In fact, the total effect, due to these practical considerations, is to modify the ideal distributed network by the introduction of lumped constants of appreciable magnitude, so that practically speaking the resultant network can be analyzed with reasonably good approximation as an equivalent capacity-inductance-resistance series circuit. The good approximation obtained from this simplification is well borne out by the 2 examples in the early part of this paper.

The following observation is of further practical interest. In the case of the ideal distributed network, Fig. 16*A*, with a load resistance $R_0 = Z$ at the discharge gap, the current at the gap would be a single rectangular discharge of duration $0.5T = 2\sqrt{L_0C_0}$ and amplitude $E/2Z$. This point is illustrated in the oscillograms of Fig. 7, but due to modifications in the distributed circuit produced by lumped circuit constants the end of the rectangle does not drop abruptly but is drawn out in an approximately exponential form.

Appendix II

Referring to Fig. 3, let the resistance of the shunt be R_s, the self and mutual inductance L_s; then, the voltage drop across the shunt set up by a current $i = f(t)$ which rises from zero to crest value and recedes gradually to zero, is

$$e = R_s f(t) + L_s \frac{d}{dt} f(t) \tag{3}$$

In general, the current rises more rapidly to crest than it recedes from crest to zero value. Then, denoting the average rise of the front as taking place in time T', for practical purposes the ratio of inductive drop superimposed on the ohmic drop is $\frac{L_s}{R_sT'}$. Therefore to eliminate a possible overshoot on the current oscillogram due to the inductive drop, the time constant $\frac{L_s}{R_s}$ of the shunt should be kept substantially smaller than the time T'. For example, in measuring a surge current rising exponentially to crest value at the initial rate of rise to crest of one microsecond, the permissible inductance for a 10 milliohm shunt should not exceed 5 millimicrohenries.

Appendix III

The surge current required just to produce fusion of a conductor is here derived from fundamental considerations. Let

$i = I_{(max)} \epsilon^{-\frac{0.693}{T}t}$, be the surge-current discharge where,

t = time in microseconds
$I_{(max)}$ = crest value of current in amperes
T = duration of current discharge from crest to half-crest value in microseconds;

and,

A = cross-sectional area of conductor in square millimeters
θ = melting point of conductor in degrees C
d = specific density of conductor
ζ = mean resistivity of conductor from zero degrees C to θ deg C
s = mean specific heat of conductor from zero degrees C to θ deg C
J = Joule's mechanical equivalent of heat = 4.18

Then from the law of conservation of energy, equating the amount of heat generated per unit length (one centimeter) of conductor by the passage of the surge current to the amount of heat per unit length of conductor required to raise its temperature from zero degrees C to θ deg C,

$$\int^{\infty} \frac{100\zeta}{A} I^2_{(max)} \epsilon^{-\frac{1.386}{T}t} dt = \frac{100\zeta}{A} \frac{I^2_{(max)} T \times 10^{-6}}{1.386} = \frac{J\theta A s d}{100}$$

$$I_{(max)} = \sqrt{(580)\frac{\theta d s}{\zeta}} \frac{A}{\sqrt{T}} \qquad (4)$$

For example, introducing the physical constants[13] of copper in the equation: $\theta = 1{,}080$; $d = 8.93$; $s = 0.117$; $\zeta = 5.30 \times 10^{-6}$

$$I_{(max)} = 350{,}000 \frac{A}{\sqrt{T}}$$

which agrees quite well with the expression obtained experimentally:

$$I_{(max)} = 320{,}000 \frac{A}{\sqrt{T}}$$

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A New Demand Meter

A new demand meter has been developed which is suitable for attaching to either a single-phase or polyphase watthour meter, and which appears to have an accuracy and all around serviceability approaching that of the watthour meter itself. It has a definite law for averaging loads, and is smooth in operation.

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VERY early in the development of the electrical industry, the watthour meter was produced. Its record for ease of maintenance and for doing continuously just what it is supposed to do is unsurpassed by any other piece of apparatus in the electrical or any other field. Millions of these meters have been manufactured and installed and kept running year after year with a minimum of maintenance cost and with unparalleled accuracy. Now, in addition to a charge for watthours, which

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is based upon the measurements of the watthour meter, it is necessary to make a charge for "ability to serve" on a "demand" basis, especially to users of large amounts of electrical energy.

The subject of demand measurement has been expounded to the fullest extent by many authors, particularly by P. A. Borden (see "The Measurement of Maximum Demand and the Determination of Load Factor," A.I.E.E. Trans., v. 39, 1920, p. 1847–83) and by Prof. P. M. Lincoln (see "Rates and Rate Making," A.I.E.E. Trans., v. 34, 1915, p. 2279–318, and "The Character of the Thermal Storage Demand Meter," A.I.E.E. Trans., v. 37, 1918, p. 189–210).

A number of different types of demand meters have been developed and have been commercially successful, but none of them has approached the ideal set by the watthour meter itself. Such an instrument should follow a definite law embodying the average loads for a given billing period and should avoid the mechanical difficulties of periodically tripping and resetting mechanisms. A new demand meter which embodies these principles is described in this paper. The record of the performance of this meter already obtained and a study of its mechanical construction indicates that it will register demand with great accuracy and, perhaps, approach the high ideal of good service set by the watthour meter.

Operation of Mechanism

The meter is suitable for attaching to either a single-phase or polyphase watthour meter. The conventional pointers for registering watthours are accompanied by a 300 deg demand scale with demand pointer and maximum hand. A representation of the principal parts of the mechanism with its connection to a watthour meter disk is given in Fig. 1, and a view of the mechanism is shown in Fig. 2. In Fig. 1, *A* and *B* are small bevel or crown gears which with a planetary gear *G* form a differential which through the relative speeds of its parts controls the angular position of the planetary gear *G* which carries with it an involute cam *C*. The cam *C* is mounted on a shaft which connects with the demand pointer *D*. A solid aluminum ball rests against the edge of the cam and is positioned between a driving disk *E* and a driven drum or roller *F*. At the "zero" position of the cam, the demand pointer is at zero on the scale and the ball is held at the exact center of the driving disk *E*. The gear *A* of the differential is driven by the watthour meter with a proper reduction in speed, and the gear *B* is driven by the drum *F* of the ball mechanism. As long as there is no load on the watthour meter, and if the ball is at the zero position, as mentioned above, the differential remains at rest and the driving disk *E* simply rotates at a constant speed due to a connection with the synchronous timing motor, but no motion is imparted to the ball and the demand pointer remains on zero.

Now, if a load is applied to the watthour meter, its side of the differential is driven at a speed proportional to this load, the cam begins to move, and since the drum *F* is tilted at a slight angle, the ball follows the cam and moves a little away from the center of the disk *E*. Immediately the ball begins to rotate about an axis which is parallel to the drum and which passes through the contact point between the ball and cam so that there is no friction at this point to prevent free rotation. Since the ball is resting on the drum *F* and rotating about a parallel axis, the drum is driven at the same surface speed as the ball and in turn drives the gear *B* in a direction which is arranged to be opposite to that of gear *A*. Thus the motion of the planetary gear *G* with the cam *C* is equal to the difference between *A* and *B*; therefore, if for any position the speed of *B* is equal to *A*, the cam remains in that position. Referring again to the position of the ball against the driving disk *E*, it is evident that the rotational speed of the ball and, consequently of the drum *F* is proportional to the distance of the ball contact point from the center of the disk *E*, which distance is exactly proportional to the angular position of the cam since the radius or "rise" of an involute cam is exactly proportional to its angular position. Then for any given load and corresponding rotational speed of *A*, there is a definite position of cam which will give an equal and opposite speed of *B*; therefore, the cam simply moves until this balance point is reached and remains there until the load on the watthour meter changes to a new value.

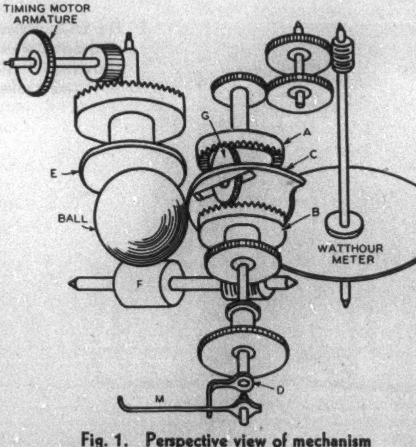

Fig. 1. Perspective view of mechanism

A. Watthour meter side of differential
B. Timing side of differential
C. Involute cam carried by center of differential
D. Demand hand
E. Ball driving disk
F. Drum driven from ball
G. Planetary gear of differential
M. Maximum hand

Since the *rate* at which the cam with the demand pointer *D* moves is equal to the difference in speed between *A* and *B*, it is evident that this rate starts off at a relatively high value then becomes less and less as A minus B approaches zero, and the time to reach the balance point fully is very long. Thus the advance of D over the demand scale is rapid at first but becomes less and less as the final position is approached. For the same change in load, the descending rate as the demand pointer returns to zero is exactly the same as the ascending rate. Thus if the watthour meter stops, the gear B simply continues to rotate and carries the cam in the reverse direction at a slower and slower speed until finally the ball is again at the center of the disk E and all motion stops.

DETERMINING LENGTH OF DEMAND PERIOD

All of the above is analogous to a thermal meter where the pointer moves at a constantly decreasing speed or rate until the escape of heat just balances the heat input due to the watts in the circuit being measured. In both cases the time element to reach the 90 per cent point is given by the equation $t = T \log \frac{1}{1 - 0.9}$ or $t = 2.302\,T$, where T is the time which would be required to reach the former balance point in the thermal meter if there were no escape of heat. Since it is impossible to avoid the escape of some heat, the time element of a given design of thermal meter may be determined and adjusted only by experiment after first building a model and operating it with various adjustments until the desired value of t is found from which the value of T may be calculated. In the new mechanical logarithmic meter under discussion, however, we may simulate the desired condition by simply stopping the synchronous motor. Then the watthour meter will carry the cam with its attendant demand pointer forward at a constant speed and will reach a given point in a time which is determined by the gear ratio between the watthour meter and the demand pointer, and which is the value of T in the above equation. As an example, suppose that a 30-min meter is desired. Then if gears are selected by which the watthour meter at full scale speed brings the pointer to full scale in 30 divided by 2.302, or 13.02 min, there results what may be called a 30-min logarithmic meter; that is, if a steady load is applied with the synchronous motor running the pointer will reach 90 per cent of its final reading in exactly 30 min. Likewise, if it is required to design a 15-min meter, the gears must be such that the pointer will reach full scale in 6.51 min with the synchronous motor stopped. For the descending or cooling curve, if the watthour meter stops, the gearing from the synchronous motor through the ball mechanism to the differential must be such that with the ball mechanism held at full scale position, the pointer will return to zero in 13.02 min and 6.51 min, respectively. Tests on this time characteristic show that this type follows the law with precision while in thermal meters there are small discrepancies due to certain physical limitations of available material and also due to the fact that heat escape is not exactly proportional to temperature.

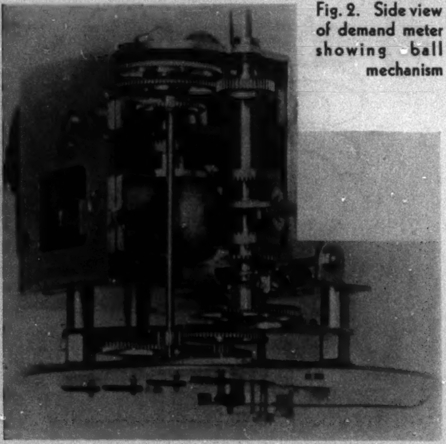

Fig. 2. Side view of demand meter showing ball mechanism

EASE OF CHECKING, AND OPERATION

Another interesting feature is the ease of checking the time element and general condition of meters in service. This new demand meter may be manually reset to zero at will and the time necessary to reach a given indication measured with a stop watch. Thus is avoided a long wait which would be necessary if the meter had to be disconnected from the load and allowed to return itself to zero along its normal logarithmic curve.

From a mechanical standpoint, the construction of the mechanism is very attractive. The operation is smooth and continuous; there is no tripping or sudden resetting or parts which might cause them to get out of order. The load on the timing motor is very small. The added load on the watthour meter can hardly be detected and is approximately the same as a standard watthour gear train. The question might be raised as to whether there is ever any slipping of the ball. In order to make certain that no slipping occurs even under the worst conditions, tests were made with the maximum hand friction adjustment tightened up until the torque required to move it was many times normal, yet there was no measurable error in the rotational speed of the ball side of the differential.

It should be apparent from the description of this instrument that the operation involves only well-known mechanical elements, such as gears, pinions, differentials, etc., a friction drive ball element such as has been in successful use for many years in a kilovoltampere demand meter, and a low speed type of synchronous motor. Therefore, it is believed that the result should be comparable in life and reliability to its associated device—the watthour meter itself.

An Economic Study of Suburban Distribution

Results of a recently completed study of methods of increasing the distribution facilities in Somerville, Mass., are presented in this paper. The economic study included several different plans covering a 10-year period, and as a result a plan is proposed which permits modification to suit future conditions.

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METHODS of providing for the relief of an existing radial substation in Somerville, Mass., a city of 105,000 population and comprising an area of approximately 4 sq miles, were recently subjected to study. Several plans for providing additional transmission, substation, and distribution facilities were considered; these included one or more of the following possibilities enlarging the present substation, building a new attended or an automatic substation, and installing a primary network with a number of different possible transformer arrangements. The 10-yr period from 1933 to 1942, inclusive, was used as a basis for the study, and consideration was given to engineering features as well as to economics.

As a result of this study, it is proposed to install initially one 2-transformer network unit at a load center in East Somerville, supplying 3 radial circuits. It is also proposed that when the load has increased sufficiently, a second 2-transformer unit be installed at another load center, with a possible interconnection of part of the radial circuits from the original and second units. A valuable feature of this plan is that still further expansion may be secured with a network system involving 2-transformer units, or by forming a network supplied by single-transformer units. The latter plan involves removing the second transformers from the original units and using them with new switching units at new locations.

Existing Facilities

The position of the existing radial substation in Somerville is shown in Fig. 1. This substation, which is located about 0.7 of a mile from the present load center, is relatively old, and contains considerable equipment which has reached the limit of its load carrying and short-circuit interrupting capacity. The firm capacity of this substation is 8,000 kva with the largest transformer bank out of service. The load is approximately 9,000 kva.

The substation is an attended station supplied by 8 13.8-kv transmission lines having a firm capacity of 30,000 kva. This excess transmission line capacity is due to the fact that initially 5 lines served the entire northern district from the L Street generating station, but with the advent of a new 110-kv substation located in this area, the load was served from the new station by means of 3 new transmission lines.

The distribution system consists of 9 4-kv 3-phase 4-wire lighting circuits having an average capacity of 1,400 kva per circuit and 4 4-kv 3-phase 3-wire power circuits with an average capacity of 1,200 kva per circuit.

Plan 1—Enlarge Present Substation

The first alternative considered was to increase the firm capacity of the present substation to 14,000 kva by the installation of another transformer bank.

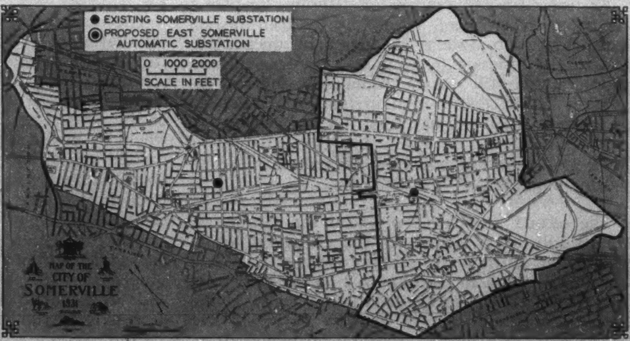
● EXISTING SOMERVILLE SUBSTATION
◉ PROPOSED EAST SOMERVILLE AUTOMATIC SUBSTATION
0 1000 2000
SCALE IN FEET
MAP OF THE CITY OF SOMERVILLE
1931

Fig. 1. Map of the city of Somerville, Mass., with East Somerville area shown outlined

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Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Nov. 22, 1933. *Not published in pamphlet form.*

In connection with this work it would be necessary to replace the existing 4-kv circuit breakers with a more modern type having a higher interrupting capacity, and to rebuild the existing 4-kv bus structure to accommodate additional distribution circuits. The ultimate development of this plan would provide for a second transformer bank to increase the firm capacity to 23,800 kva. At this time it would be necessary to add another 13.8-kv bus section and to replace the existing 13.8-kv circuit breakers with a more modern type having a higher interrupting capacity, but it would not be necessary to add any more transmission lines. Another section would be added to the 4-kv bus to provide for additional distribution circuits.

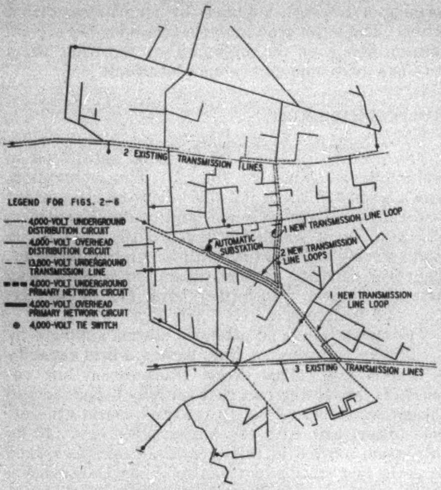
2 EXISTING TRANSMISSION LINES
LEGEND FOR FIGS. 2–6
4,000-VOLT UNDERGROUND DISTRIBUTION CIRCUIT
4,000-VOLT OVERHEAD DISTRIBUTION CIRCUIT
13,800-VOLT UNDERGROUND TRANSMISSION LINE
4,000-VOLT UNDERGROUND PRIMARY NETWORK CIRCUIT
4,000-VOLT OVERHEAD PRIMARY NETWORK CIRCUIT
4,000-VOLT TIE SWITCH
1 NEW TRANSMISSION LINE LOOP
AUTOMATIC SUBSTATION
2 NEW TRANSMISSION LINE LOOPS
1 NEW TRANSMISSION LINE LOOP
3 EXISTING TRANSMISSION LINES

Fig. 2. Transmission and distribution systems for automatic substation (initial and ultimate installation, plan 3)

Transmission and distribution diagrams for plan 1 are not presented here, as initially the transmission and distribution systems would remain unchanged, and in the ultimate development the transmission system would still remain unchanged, and the expansion of the distribution system would depend upon the location and nature of the load growth.

PLAN 2—ABANDON PRESENT SUBSTATION AND BUILD NEW SUBSTATION

The second alternative provided for a new, attended substation located at the estimated future load center which would contain one new 7,500-kva transformer bank in addition to 2 5,250-kva banks taken from the present substation, thereby giving the new substation a firm capacity of 12,000 kva based upon zero degrees C ambient temperature, under which condition the 7,500-kva banks were given an overload rating of 9,800 kva, and the 5,250-kva banks were given an overload rating of 6,000 kva.

Transmission lines feeding the present substation would be extended to the new location, there terminating in 2 13.8-kv bus sections equipped with 350,000-kva circuit breakers.

Initially there would be 3 4-kv bus sections equipped with 150,000-kva circuit breakers and accommodating 21 distribution circuits, 16 of which would be completely equipped. The distribution circuits themselves would consist of 350,000-cir-mil feeder cables installed from the substation to pick up the existing distribution circuits.

The ultimate development provides for the installation of another 7,500-kva transformer bank to increase the firm capacity to 21,800 kva. The 13.8-kv busses would not be altered, but another section would be added to the 4-kv bus thereby providing for a total of 28 distribution circuits, 23 of which would be completely equipped. The necessary 4-kv circuits would consist of 350,000-cir-mil feeder cables run out to their respective load centers from which point the distributors would be extended to pick up the load.

Transmission and distribution diagrams for plan 2 are not presented here, for the same reasons that they were omitted for plan 1.

PLAN 3—BUILD NEW AUTOMATIC SUBSTATION

The next alternative considered was to maintain the existing substation at its present capacity of 8,000 kva initially, and to supplement it with a new automatic substation, located approximately 1.5 miles from the first. It was proposed to install 2 7,500-kva transformer banks and 2 13.8-kv bus sections in the new station supplied from loops of 2 nearby transmission lines. This would give the new substation a firm capacity of 9,800 kva, and in order to distribute this energy it was proposed to install 1 4-kv bus section to provide for 7 distribution circuits, 4 of which would be completely equipped. The 4-kv circuits would consist of 350,000-cir-mil feeders installed out to load centers as shown in Fig. 2.

The ultimate development would provide for the installation of a new 7,500-kva transformer bank in the present substation which would necessitate the changing of the existing 4-kv breakers to a more modern type. This would increase the firm capacity of the system to 23,800 kva, 9,800 kva of which would be in the new substation, and 14,000 kva in the old substation. Under these conditions, 2 new 350,000-cir-mil 4-kv feeder cables would be installed to their respective load centers in order to pick up the additional load.

The completion of this work would provide 2 modern substations with combined firm capacity to supply the 10-year ultimate load in Somerville, with consequent increased reliability of service, decreased distribution costs, and reduced interrupting duty on all circuit breakers.

PLANS 4 AND 5—PRIMARY NETWORK SCHEME

The Boston Edison Company has had in operation since February 1932, a primary network system supplied from 3 1,500-kva network units in the Brighton and Brookline area which was installed after an extensive study had shown it to be the most suitable method of providing relief for the existing overloaded substation supplying this area. In view of its highly successful operating experience with this network, and also as a result of comparative studies made for supplying service to an entirely new area both by means of a radial substation and by a primary network system, in which the network showed a saving of approximately 20 per cent over the radial system, it was decided to make a study of the possibility of relieving the existing Somerville station of some of its load by the installation of a primary network.

An area comprising approximately 1.5 sq miles in East Somerville was chosen for this study. This is the area enclosed with the heavy line in Fig. 1. The peak load in this area, which is approximately 3,700 kva is now supplied by 4 3-phase 4-wire lighting circuits and 3 3-phase 3-wire power circuits, with a total of 10.6 circuit miles of overhead construction and 5.6 circuit miles of underground construction.

It was proposed to install network units which would have a normal rating of 2,000 kva with blower equipment and a rating of 2,500 kva under ambient conditions of zero degrees C, either in underground vaults, or above ground on concrete mats, depending upon local conditions. On this basis the installation of 3 primary network units would provide a firm capacity of 5,000 kva with one unit out of service, which would take care of the initial demands and provide considerable spare capacity. Preliminary costs showed, however, that the increased cost of this street work over that of a similar 4-unit network, due to the less favorable locations of the units with respect to existing copper, would nearly offset the additional cost of the fourth unit, and as a 4-unit network has certain inherent advantages over one with 3 units, no diagrams or further studies were made for the latter scheme.

A transmission and distribution system diagram for the initial network installation is given in Fig. 3, showing the location of the 4 primary network units, transmission lines, network mains, taps, and tie connections to existing radial circuits. A similar diagram for the ultimate network installation supplied from 6 primary network units is given in Fig. 4. Taps from the network mains have been omitted from this diagram due to the uncertainty of the location and nature of the load growth.

In practically all cases sufficient conductors were available to form a 4-wire main between units by combining existing power and lighting circuits and removing the extra conductors. In no case was it necessary to increase the size of any of the conductors, as No. 1/0 was the smallest size encountered and previous studies have indicated that this size is sufficient for all network needs. Very little rephasing was required as the single-phase circuits were taken over intact and the 3-phase transformers cut over where necessary.

PLANS 6 AND 7—RADIAL CIRCUITS SUPPLIED FROM NETWORK UNITS

During the progress of the network study it became more and more apparent from the nature and the location of the load, and from the location and

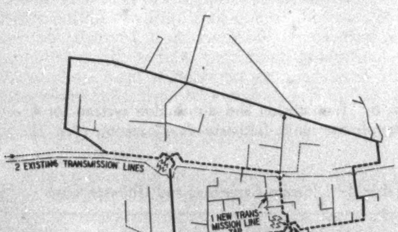
2 EXISTING TRANSMISSION LINES
1 NEW TRANSMISSION LINE TAP
PRIMARY NETWORK UNIT
3 EXISTING TRANSMISSION LINES

Fig. 3. Transmission and distribution systems for 4 single-transformer network units (initial installation, plan 5)

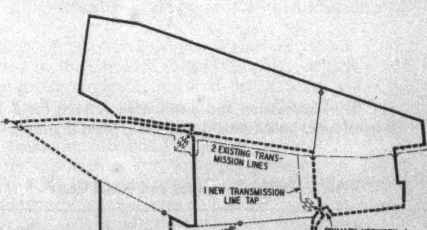
2 EXISTING TRANSMISSION LINES
1 NEW TRANSMISSION LINE TAP
PRIMARY NETWORK UNIT
1 NEW TRANSMISSION LINE TAP
3 EXISTING TRANSMISSION LINES

Fig. 4. Transmission and distribution systems for 6 single-transformer network units (ultimate development, plans 5 and 6)

arrangement of the existing transmission lines and 4-kv distribution circuits, that there was sufficient justification to warrant the making of a study for supplying the load in this same area by means of radial circuits supplied from primary network units.

It was proposed to add a second transformer to a standard network unit and connect it to the 4-kv bus through one of the feeder circuit breakers, thereby leaving 3 breakers available for distribution circuits. This second transformer would be supplied from a separate transmission line so that each 2-transformer unit would have a firm capacity with one line out of service of 2,500-kva.

These 2-transformer units would be installed above ground, either on concrete mats using weatherproof units, or the switch units themselves might be installed in a small building.

One very attractive feature of this plan lies in the fact that an existing radial system can be relieved of approximately 2,500 kva of load at a relatively small cost by the installation of one of these 2-transformer units at some load center where short 4-kv feeders can conveniently be run out to pick up existing distributors. As the load continues to grow, a second 2-transformer unit can be installed at another load center, as in Fig. 5. Two of the circuits out of this unit can be arranged for interconnection with 2 circuits out of the first unit, if short-circuit studies show that satisfactory relaying

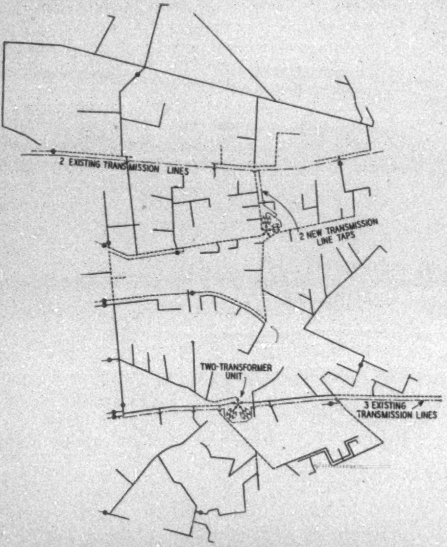
2 EXISTING TRANSMISSION LINES
2 NEW TRANSMISSION LINE TAPS
TWO-TRANSFORMER UNIT
3 EXISTING TRANSMISSION LINES

Fig. 5. Transmission and distribution systems for 2 2-transformer units (initial installation, plans 6 and 7)

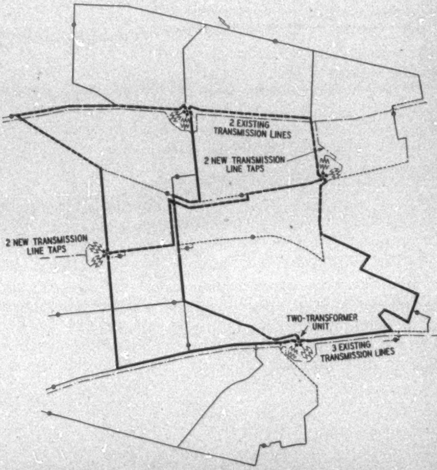
2 EXISTING TRANSMISSION LINES
2 NEW TRANSMISSION LINE TAPS
2 NEW TRANSMISSION LINE TAPS
TWO-TRANSFORMER UNIT
3 EXISTING TRANSMISSION LINES

Fig. 6. Transmission and distribution systems for 4 2-transformer units (ultimate development, plan 7)

Table I—Initial Capacities and Initial Costs

Method of Providing Capacity	Firm Capacity	Cost*	Per Cent of Plan No. 2
1. Enlarge and rebuild present substation	14,000 kva	$182,250	30.6
2. Abandon present substation and build new substation	12,000 kva	596,750	100.0
3. Maintain present substation and build new automatic substation	17,800 kva	335,700	56.2
4. Maintain present substation and install primary network with 3 single-transformer units	13,000 kva	212,050	35.6
5. Maintain present substation and install primary network with 4 single-transformer units	15,500 kva	235,500	39.4
6. Maintain present substation and install primary network starting with one 2-transformer unit	10,500 kva	77,000	12.9
7. Maintain present substation and install primary network starting with one 2-transformer unit	10,500 kva	77,000	12.9

* These cost figures include land costs as well as costs for station and street work.

Table II—Ultimate Capacities and Ultimate Costs

Method of Providing Capacity	Firm Capacity	Cost*	Per Cent of Plan No. 2
1. Enlarge and rebuild present substation	23,800 kva	$433,750	56.0
2. Abandon present substation and build new substation	21,800 kva	773,000	100.0
3. Maintain present substation and build new automatic substation	23,800 kva	520,000	67.4
4. Maintain present substation and install primary network (grown from 3 to 6 single-transformer units)	20,500 kva	379,550	49.1
5. Maintain present substation and install primary network (grown from 4 to 6 single-transformer units)	20,500 kva	362,000	46.8
6. Maintain present substation and install primary network (grown from one 2-transformer unit to 6 single-transformer units)	20,500 kva	362,000	46.8
7. Maintain present substation and install primary network (grown from 1 to 4 2-transformer units)	23,000 kva	330,000	42.7

* These cost figures include land costs as well as costs for station and street work.

Table III—Plan No. 1; Enlarge Present Substation

Year	Station	Land	Street	New Investment	Fixed Charges at 12.5%	Present Value at 7%	Present Value at 15%
1933	$182,250			$182,250	$ 22,800	$ 22,800	$ 22,800
1934					22,800	21,300	19,800
1935					22,800	19,900	17,230
1936					22,800	18,600	15,000
1937					22,800	17,400	13,080
1938	32,000		$20,000	234,250	29,300	20,900	14,580
1939					29,300	19,500	12,680
1940					29,300	18,250	11,000
1941	179,500		20,000	433,750	54,200	31,550	17,700
1942					54,200	29,500	15,380
					$310,300	$219,700	$159,250

Table IV—Plan No. 2; Abandon Present Substation and Build New Substation

Year	Station	Land	Street	New Investment	Fixed Charges at 12.5%	Present Value at 7%	Present Value at 15%
1933	$491,750	$15,000	$90,000	$596,750	$ 74,500	$ 74,500	$ 74,500
1934					74,500	69,600	64,800
1935					74,500	65,100	56,300
1936	126,250		50,000	773,000	96,600	78,800	63,500
1937					96,600	73,700	55,400
1938					96,600	68,900	48,200
1939					96,600	64,400	41,800
1940					96,600	60,200	36,350
1941					96,600	56,300	31,600
1942					96,600	52,600	27,500
					$899,700	$664,100	$499,950

Table V—Plan No. 3; Maintain Present Substation and Build New Automatic Substation

Year	Station	Land	Street	New Investment	Fixed Charges at 12.5%	Present Value at 7%	Present Value at 15%
1933	$206,700	$35,000	$94,000	$335,700	$ 41,900	$ 41,900	$ 41,900
1934					41,900	39,200	36,450
1935					41,900	36,600	31,700
1936					41,900	34,200	27,550
1937					41,900	32,000	24,000
1938			55,000	390,700	48,850	34,800	24,350
1939					48,850	32,550	21,150
1940					48,850	30,400	18,350
1941	167,000		5,000	562,700	70,350	41,000	23,000
1942					70,350	38,350	20,000
					$496,750	$361,000	$268,450

Table VI—Plan No. 4; Maintain Present Substation and Establish Primary Network (3 Units Originally)

Year	Station	Land	Street	New Investment	Fixed Charges at 12.5%	Present Value at 7%	Present Value at 15%
1933	$126,000	$13,000	$73,052	$212,052	$ 26,500	$ 26,500	$ 26,500
1934					26,500	24,800	23,050
1935					26,500	23,150	20,000
1936					26,500	21,600	17,400
1937	42,000	4,500		258,552	32,350	24,650	18,500
1938					32,350	23,050	16,100
1939					32,350	21,550	14,000
1940	42,000	2,000	16,500	319,052	39,850	24,800	15,000
1941					39,850	23,250	13,030
1942	42,000	1,500	17,000	379,552	47,450	25,850	13,500
					$330,200	$239,200	$177,080

would result, thereby forming a network supplied from 2 5,000-kva units with a firm capacity of 7,500-kva. This system later can be expanded into either a network supplied from several 2-transformer units as in Fig. 6, or one of the transformers may be removed from each of the existing units, combined with a new switching equipment and relocated to form a network supplied from single-transformer units, as previously shown in Fig. 4.

METHOD OF ECONOMIC COMPARISON

From an economic standpoint the network scheme offers marked advantages, as may be seen from Table I, which is based upon accurate estimates obtained from the construction bureau of the company for the station and street work in accordance with the description of each as given in this paper. The costs of distribution transformers, secondary services, and other common costs are omitted for each plan.

The first step in this economic study consisted of extending the peak kilovoltampere load curve to 1942, giving the proportionate amount of weight to such factors as rate of increase of population, increase in the number of customers, and in the number of houses assessed, houses wired and the building trend; from this curve it was estimated that the load would increase approximately at the rate of 7 per cent per year over that period. However, in view of the uncertainty of predicting load growth, and realizing the importance of its effect on the installation of additional capacity, studies were made for load growths of 5, 7.5, and 10 per cent, but as each study showed the same relative order of magnitude for each scheme, only the study for the 7.5 per cent load growth is included in this paper.

Each of the alternatives shown in Table I was carried to its ultimate (1942) capacity, which would be approximately 20,000 kva based upon a 7.5 per cent load growth, by the addition of capacity when needed. For convenience, these ultimate capacities and costs are tabulated in Table II.

The tabulations for each plan, shown in Tables III to IX, inclusive, which are presented primarily to show the annual costs incurred by each investment, are separated into 4 columns, as follows:

1. New investment.

2. Annual costs. These are the fixed charges based upon a certain percentage of the new investment. The rate was taken at 12.5 per cent and includes interest, taxes, and depreciation. No account was taken of energy losses or maintenance, as it was felt that the differential in costs for these items would not be sufficient to affect the relative magnitude of the total costs for the several plans appreciably.

3. Present worth of yearly costs. In order to make proper allowance for the effect of interest in comparing yearly costs occurring in different years, the annual costs have been discounted at 7 per cent compounded annually, and these figures are shown as the present worth of yearly costs.

4. Discounted present worth of yearly costs. In view of the unknown effect of future occurrences on the outcome of present plans, it was felt that the results would be progressively less accurate for the later years, and therefore in making any choice between the various alternatives, the later years should be given less weight than

Table VII—Plan No. 5; Maintain Present Substation and Establish Primary Network (4 Units Originally)

Year	Station	Land	Street	New Investment	Fixed Charges at 12.5%	Present Value at 7%	Present Value at 15%
1933	$168,000	$17,500	$50,000	$235,500	$ 29,400	$ 29,400	$ 29,400
1934					29,400	27,500	25,580
1935					29,400	25,700	22,200
1936					29,400	24,000	19,320
1937					29,400	22,450	16,830
1938					29,400	20,950	14,600
1939					29,400	19,600	12,700
1940	42,000	1,500	18,000	297,000	37,100	23,100	13,950
1941					37,100	21,650	12,120
1942	42,000	3,000	20,000	362,000	45,250	24,650	12,870
					$325,250	$239,000	$179,570

Table VIII—Plan No. 6; Maintain Present Substation and Establish Primary Network (2-Transformer Radial Units Originally)

Year	Station	Land	Street	New Investment	Fixed Charges at 12.5%	Present Value at 7%	Present Value at 15%
1933	$ 55,000	$ 2,000	$20,000	$ 77,000	$ 9,625	$ 9,625	$ 9,625
1934	55,000	3,500	25,000	160,500	20,050	18,700	17,400
1935					20,050	17,500	15,180
1936					20,050	16,350	13,200
1937	58,000	12,000	5,000	235,500	29,400	22,450	16,850
1938					29,400	20,950	14,620
1939					29,400	19,600	12,710
1940	42,000	1,500	18,000	297,000	37,100	23,100	13,960
1941					37,100	21,600	12,110
1942	42,000	3,000	20,000	362,000	45,250	24,650	12,880
					$277,425	$194,525	$138,535

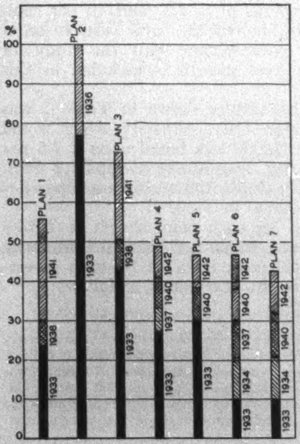

Fig. 7. Initial, increment, and ultimate investment costs for supplying city of Somerville, 1933–1942

Annual load growth assumed 7.5 per cent

the earlier years. The figures which take this factor into consideration are prepared in the same manner as the figures for "present worth of yearly costs," except that a factor of 15 per cent per year compounded annually was used, 7 per cent of which was for interest and 8 per cent for relative inaccuracy.

The one outstanding fact which is forcibly brought out by a careful study of these tabulations is that any scheme which makes maximum use of existing capacity and adds capacity in small increments will have the lowest initial cost and also the lowest annual carrying charges. This is shown graphically in Figs. 7 and 8. A summary of the annual costs is given in Table X.

Table IX—Plan No. 7; Maintain Present Substation and Establish 2-Transformer-Unit Primary Network (2-Transformer Radial Units Originally)

Year	Station	Land	Street	New Investment	Fixed Charges at 12.5%	Present Value at 7%	Present Value at 15%
1933	$ 55,000	$ 2,000	$20,000	$ 77,000	$ 9,625	$ 9,625	$ 9,625
1934	55,000	3,500	25,000	160,500	20,050	18,750	17,420
1935					20,050	17,500	15,180
1936					20,050	16,350	13,200
1937					20,050	15,300	11,500
1938					20,050	14,300	10,000
1939					20,050	13,350	8,670
1940	55,000	7,500	25,000	248,000	31,000	19,300	11,660
1941					31,000	18,100	10,130
1942	55,000	2,000	25,000	330,000	41,250	22,450	11,730
					$233,175	$165,025	$119,115

Table X—Summary of Annual Costs

Plan No.	Fixed Charges at 12.5%	Present Value at 7%	Present Value at 15%
1	$310,300	$219,700	$159,250
2	899,700	664,100	499,950
3	496,750	361,000	268,450
4	330,200	239,200	177,080
5	325,250	239,000	179,570
6	277,425	194,525	138,535
7	233,175	165,025	119,115

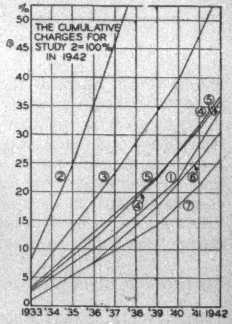

Fig. 8. Cumulative annual carrying charges for various methods of supplying city of Somerville, 1933–1942

Annual load growth assumed 7.5 per cent
Annual carrying charges 12.5 per cent

CONCLUSIONS

As a result of the foregoing considerations, both engineering and economic, it is proposed to provide initially for the relief of the existing substation supplying Somerville by means of one 2-transformer network unit located at a load center in East Somerville and supplying 3 radial circuits. Plans 6 and 7 are based upon this initial arrangement. Later, when the load justifies it, a second 2-transformer unit is to be installed at another load center nearby, and 2 of its radial circuits will be so arranged that they may be interconnected with 2 of the circuits from the original unit if found practicable. Beyond this point, the decision to expand the system into a network by the installation of additional 2-transformer units, or by removing the second transformers from the original units and combining them with new switching units at new locations to form a network supplied by single-transformer units, will be governed by conditions which may arise at that time.

The ability to expand this system by the method which will be most advantageous at such time as any expansion may become necessary, appears to be the most valuable feature of this proposed plan.

The authors wish to acknowledge the valuable assistance rendered by J. F. Maxwell, L. J. Weed, and St. G. T. Arnold in assembling and arranging the material for this paper.

The Pitt-Westinghouse Graduate Program

Recognizing that some of the highest types of graduate engineering instruction is to be found in a few of the larger research and industrial organizations, the University of Pittsburgh (Pa.) and the Westinghouse company during the past several years have coöperated in a joint program of graduate study for certain designated employees of the company. Besides being of distinct benefit to the individual employee, this work has had a highly stimulating influence upon the faculty members of the university connected with it, and the results have been most gratifying to the industry.

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TO THOSE who have been identified with engineering education in the Pittsburgh (Pa.) district for the past 25 years, the formal presentation of the University of Pittsburgh-Westinghouse graduate program in 1927 was a logical step forward in higher education. It is interesting to note that in 1910 2 highly significant events took place: (1) The University of Pittsburgh introduced the coöperative system of undergraduate engineering education on a plan somewhat different from that in use at the University of Cincinnati; (2) Mr. B. G. Lamme, then chief engineer of the Westinghouse Electric and Manufacturing Company, was formulating an intensive program of educational work for the highly selected group of engineering graduates received by the Westinghouse company each year. These 2 ideas, apparently unrelated, have been adopted during the years by many educational and industrial institutions. It seemed, therefore, an obvious move to correlate these activities under the general direction of the graduate school of the University of Pittsburgh, and it is now widely known in educational circles as the University of Pittsburgh-Westinghouse graduate program.

The following quotation is taken from a recent publication of the graduate school of the University of Pittsburgh:

> ". . . it is realized that a general undergraduate education was never designed, and never should be designed, to prepare individuals for immediate, highly specialized service. First must be laid the broad foundation without which graduate work would be but a mockery. But the foundation once laid, the peculiar services which a graduate school can render become self-evident."

This quotation is cited primarily to show the breadth of view held by Dr. L. P. Sieg, dean of the graduate school of the University of Pittsburgh since 1925. Doctor Sieg maintains that some of the highest type of graduate instruction is to be found in a few of the larger research and industrial organizations. As already indicated, this idea has been accepted for years by many engineering faculties in undergraduate training, in some form of coöperative work. It remained, therefore, to work out a similar plan to assimilate some of the higher grade industrial instruction available in the Pittsburgh district. Considering the usual method of pedagogic administration in many graduate schools, it is not surprising that this plan has created widespread discussion.

It is realized that there are not many places equally favored by the circumstances cited and it therefore is not possible to establish a similar practice at all universities; but the salient features of the arrangement so eminently are suited to meet the basic requirements of a postgraduate engineering

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Full text of a paper recommended for publication by the A.I.E.E. committee on education, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 23–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Dec. 5, 1933. *Not published in pamphlet form.*

education that similar plans elsewhere, even on a smaller scale, should be well worthwhile.

In discussing the fundamentals of an adequate engineering education, it is well to recognize the fact that the requirements for the engineering profession are different from those of some of the older professions. Frequently the latter are regarded as being essentially professions of learning; and since the methods of the universities are naturally the outgrowth of practices evolved in the older professions, there is an inclination to overemphasize the importance of book learning in engineering training. Now, regardless of how important knowledge may be in any walk of life, including engineering, of course, it nevertheless should be recognized clearly that the engineering profession is primarily a profession of creation and accomplishment and that the training of engineering students and of the younger engineers therefore should be directed toward developing in them above all else a desire and ability to create and accomplish. It is extremely important, then, that in addition to imparting the necessary knowledge, particular stress be laid upon developing in the student during the most formative period of his life such traits as initiative, action, imagination, analytical ability, and independence of thought; in other words, accomplishment through knowledge rather than knowledge in itself should be stressed throughout the entire course, beginning even during the undergraduate program as far as at all possible. However, no matter how carefully the curriculum may be planned and how thoroughly the college work carried out, it will have to be admitted that it is at best very difficult to give to the student in a purely university atmosphere that training in developing initiative, resourcefulness, action, and responsibility which is required in actual practice. Consequently, there is a distinct danger in extending the engineering college course beyond the usual 4-yr program, except for those who expect to make research or teaching their life work. The inevitable conclusion is that postgraduate work on subjects that cannot be covered adequately during the undergraduate course should be carried on by engineers after entering the profession.

Although many universities have established postgraduate evening courses, seldom is it found that the individual student avails himself of more than 1 or 2 courses, or that such work is extended over a very long period after graduation. The only way in which this condition can be improved is by offering proper incentives for postgraduate work, preferably in the form of additional university degrees. If these incentives are to be effective and accomplish the maximum results, they must be such as to stimulate an appreciable number of engineers to greater effort than that involved in 1 or 2 casual graduate courses. In this connection, there is one fundamental which should govern the establishing of standards for offering degrees or similar incentives of any kind, and that is that the standards should be such as to bring about the maximum total effort in the profession and therefore result in maximum accomplishment as a whole. It is all very well to establish a high standard; but if the standard is so high that only exceptional students can reach it, little good will be accomplished. The same is true if the conditions are such that the possibilities are open only to students in favorable financial circumstances. In short, the conditions and standards governing the obtaining of degrees should be such that the goal is possible of attainment by a reasonably large number of the abler members of the profession. Furthermore, degrees in engineering should be conferred as rewards for originality and accomplishment rather than for the accumulation of knowledge alone, if they are to take cognizance of the requirements of the engineering profession.

The University of Pittsburgh-Westinghouse graduate program recognizes these fundamentals, as shown in the following regulations published by the graduate school of the University of Pittsburgh:

> "By agreement between the Westinghouse Electric and Manufacturing Company and the graduate school, certain courses in the educational program of the company are identified with the school. Those in charge of the administration and of the instruction of these courses have regular appointments on the staff of the University of Pittsburgh, and hence credits earned in these courses are recorded under the regulations as resident credits. Regardless of the number of credits earned in the Westinghouse courses, there must be gained for the master's degree a minimum of 10 credits in regular University courses and 6 thesis credits.
>
> "1. Courses are open, except by special permission, only to designated employees of the Westinghouse Electric and Manufacturing Company who are graduates of accredited colleges or universities.
>
> "2. Registration, including the payment of fees, shall be effected at the University of Pittsburgh.
>
> "3. No student may take any of the Westinghouse courses for credit in the graduate school, unless he has in advance the approval of the dean of the graduate school and of the head of his major department.
>
> "4. A registration fee of $5 for each registration is required regardless of the number of courses taken. For the Westinghouse courses, there is no tuition charged, but for the courses offered by the resident staff of the University of Pittsburgh, the regular tuition charges are levied. Upon the granting of a degree, the regular graduation and publication fees are also assessed.
>
> "5. Credits earned through the Westinghouse courses are recorded as resident credits
>
> "6. A minimum of 30 resident credits is required for any degree from the University, of which, in this particular arrangement, a minimum of 16, if the thesis is worked out on the campus, must be earned in campus courses.
>
> "7. The research work leading to a thesis may be conducted with the consent of the head of the department, under the direction of any of the Westinghouse lecturers."

As indicated in these regulations, there are at present 30 Westinghouse lecturers actively identified with this program. As such, they are recognized members of the graduate faculty of the University, meeting from time to time as a group with the resident faculty.

The 30 credits required for the master's degree normally would take at least 5 or 6 years of evening work even under the most ideal conditions, assuming that suitable evening courses were available during such an extended period of time. Such sustained effort and continued financial sacrifices for tuition and the like, particularly during early life, makes the obtaining of a master's degree impracticable, if not impossible, in the majority of cases. With the plan described, it is quite possible with reasonable effort outside of business hours and under moderate financial obligations to obtain this degree in about 3 years. At the same time, the total requirements in the way of university credits have not been lessened in the least and the thesis requirements have been increased.

With reference to the thesis, it must be considered that the laboratory facilities now existing in the larger industries will permit the carrying on of work of a character often impossible with the facilities available in the colleges; consequently, the thesis results accomplished are likely to be of a character often impossible with the facilities available in the colleges, and therefore are likely to be, but not necessarily, of a higher order and of greater usefulness. The fact that the work carried on in industry is to serve as the basis for a thesis will prove an incentive for the use of a higher order of analytical work and originality. Consequently, the results will be of greater value to the industry, and the engineer himself will profit because of the necessity for greater accomplishment and for carrying such additional studies as are required for his thesis. Appendix II gives a list of these subjects so far completed as a part of this program. As a rule, the thesis work is carried on under available research or development appropriations of the company, although at times small special appropriations are made for the purpose; therefore, no expense to either the student or the university is involved. Where appropriations for experimental work cannot be made available, a purely analytical study often is chosen for the thesis. The work usually is supervised by one of the University of Pittsburgh-Westinghouse lecturers after formal approval has been granted by the department of electrical engineering of the university.

Dr. E. A. Holbrook, dean of the schools of engineering and mines of the University of Pittsburgh, says:

> "During the past 4 years I have reviewed a number of the theses presented by candidates for the master's degree under our Westinghouse coöperative graduate program. Uniformly, these theses show more professional maturity and higher research technique than the usual postgraduate master's theses in engineering. I make this comparison, having in mind not the University of Pittsburgh alone, but also the graduate theses I have read in the several colleges with which I have been connected."

A general idea of the character of the courses of study can be obtained from Appendix I. Many of these consist of lecture courses and problem work, although in several the problem work predominates. In general the courses are conducted in a manner quite similar to the regular university courses, except that most of them are given during working hours and some of them at night. The course *E.E. 151–152W* on electrical theory and engineering practice, which is an outcome of the so-called engineering school of the Westinghouse company, is somewhat different from the ordinary course. It consists of weekly assignments of a relatively large number of questions which the students are called upon to answer during an extended quiz at the end of the week. The questions represent broadly a survey of the present state of the electrical art and accumulated experience in the application of fundamental principles to engineering problems. They involve the study of designs, materials, methods of construction, testing, application, and maintenance of a wide variety of electrical appliances and equipment, as well as significant excursions into the history of the development of the art. This part of the graduate program, as well as many other features, has grown out of the pioneering work in advanced engineering education by Mr. B. G. Lamme; some of Mr. Lamme's fundamental ideas along this line are set forth in his publications. (See "Technical Training for Engineers," *Electric Journal*, Sept. 1916, p. 404.)

Among the courses instituted during the more recent years, special attention might be called to *E.E. 193W* by Doctor Slepian on conduction of electricity in gases, *E.E. 181–182W* by Doctor Lewis on symmetrical components, and *M.E. 161–162W* by Doctor Nadai on applied elasticity. Complying with an urgent demand, these courses and also the one on electrical theory and engineering practice have been made available to students outside of the Westinghouse company and an appreciable number of engineers connected with the utilities and also instructors and postgraduate students of the university have availed themselves of this opportunity.

Special attention is called to the fact that credits can be obtained only by successful completion of these various courses. No credits whatsoever are obtained for any of the shop, testing, drafting, or engineering work done by the students during working hours. The experimental work for the theses is conducted, of course, in the laboratories of the company during working hours, and frequently the engineering work of the company benefits from the solution of the problems in connection with the theses.

The entire work of the students is done under the broad guidance of the school of engineering of the university, and the university assumes the responsibility for the adequacy of the program. However, since a great many of the engineering subjects required for the master's degree are given by the Westinghouse staff, the evening courses covered by the university staff relate essentially to such subjects as advanced physics, mathematics, economics, and the like, so that a properly balanced curriculum will be maintained. The degree conferred is that of Master of Science, usually with the major in electrical or mechanical engineering.

In 1930 the plan was extended to include the doctor's degree, the requirements for which, although in the first stages similar to those for the master's degree, are more extensive both in quantity and quality of work to be covered. For the doctor's degree great care is exerted to select candidates who have much more than the capacity to pursue courses and to conduct simple, straightforward research. It is felt that, for the most part, the investigations and courses should be carried on in the fundamental fields of physics, mathematics, or chemistry. Although for the master's degree certain credits can be obtained through Westinghouse courses and research work, the majority of the credits for the doctor's degree have to be obtained through the university courses.

Tables I, II, and III give some statistical data relating to the graduate program and the results obtained. Table I gives the number of degrees granted during successive years. Table II indicates that a total of 354 students have participated in this work and 59 or only about $^1/_6$ of that number have obtained degrees. Some pertinent conclusions may be drawn on the basis of these figures:

1. Requirements for the degrees are high, which means that, in addition to the necessary analytical ability, a great amount of energy and perseverance is needed.
2. Distracting influences are encountered due to increasing professional and family responsibilities.
3. Depression readjustments and low financial resources have prevented some from completing the work.
4. Under normal conditions, many students are transferred to distant branches of the company, and although the university has arranged reciprocal relations with other graduate schools, the resultant progress is slower.

Table III shows that in addition to the fact that approximately 50 per cent of the graduates remain with the company, about 25 per cent are called into teaching or some phase of educational work.

Table I—Degrees Awarded

Year	M. S.	Ph.D.
1927	1	
1928	1	
1929	8	1
1930	9	
1931	14	
1932	12	1
1933	11	1
Total	56	3

From the standpoint of the industry, the results of this postgraduate work have been most gratifying. Although the average engineering graduate is inclined to settle down to routine work after entering industry, an entirely different spirit can be noted among those taking part in this postgraduate work. During the various courses their interest in analytical work is maintained, and the necessity for taking the initiative in their thesis work develops a definite self-confidence in their ability to do original and advanced analytical work. As a consequence, all of their later engineering work is influenced along similar lines. It is noted also that of the various papers presented by the company engineers before the different professional societies, a large percentage is supplied by engineers who either are on the Westinghouse teaching staff or who have completed successfully their work for the master's or doctor's degree in this coöperative course.

Table II—Total Earned Credits

	No. of Individuals	
Less than 6 credits	106	
6–10 credits	53	
11–14 credits	38	
15–23 credits	80	
Less than 24 credits		277
Exactly 24 credits	23	
More than 24 credits	54	
Number with sufficient credit for degree		77
Total participants		354
Degrees granted		59
Credit requirement complete for master's degree		18

Table III—Present Location of Those Who Have Received Degrees

Westinghouse Elec. and Mfg. Co.	30
Teaching and educational work	15
Other work	14
Total	59

With reference to the university, this coöperative program is found to be of benefit in so far as it has a highly stimulating influence upon the faculty members connected with the work. It has made possible courses that would not have been possible without such a plan; in some cases this coöperation has led to certain mathematical courses prepared jointly by a member of the university staff and one of the industrial staff, with the result that the application of mathematics to practical engineering problems has been presented more effectively to the students.

Appendix I—Descriptions of Courses

The following course descriptions have been taken from the last edition of the "Graduate School Bulletin" of the University of Pittsburgh; they illustrate the advanced nature of the technical content of the various Westinghouse courses and the credits allowed.

EE 151W. Electrical Theory and Engineering Practice, I; 2 credits. A study of theory of operation and standards of practice in design, manufacture, and application of electrical equipment, generators, motors and their control, thermionic tubes, oscillographs, voltage regulators, relays, and transformers. *Hellmund and Dudley.*

EE 152W. Electrical Theory and Engineering Practice, II; 2 credits. A second course similar in character to *EE 151W*, but embracing synchronous converters, materials and processes, refrigeration, railway motors, circuit breakers, switches and fuses, lightning arresters, heating appliances, capacitors, switchboards, and rectifiers. *Hellmund and Dudley.*

EE 161W. Electrical Machine Design, I; 2 credits. Fundamental equations for the generated emf. The distribution of the magnetizing flux is determined by rigid graphical solutions. The mmf's of distributed windings by mathematical and graphical methods. The effect of pulsations and harmonics of the mmf's. Flux analysis for 2-dimensional fields. Calculation of saturation curves. *Laffoon and Calvert.*

EE 162W. Electrical Machine Design, II; 2 credits. A quantitative analysis of the theory of commutation for both direct and alternating current machines. Detailed treatment of commutation as a switching problem, secondary phenomena affecting commutation, etc. *Hellmund, Baker, and Labberton.*

EE 163W. Electrical Machine Design, III; 2 credits. A study of the constants of alternating current machines which determine the transient and continuous operating characteristics. Development of formulas for calculating constants. The special problems of synchronous machine design. *Dudley, Shutt, and Kilgore.*

EE 164W. Electrical Machine Design, IV; 2 credits. Consideration of the fundamental laws of magnetism and of the magnetic and electrical properties of core materials, with their adaptations to electrical apparatus. *Spooner.*

EE 165W. Electrical Apparatus Design; 2 credits. The fundamentals of design of magnets and transformers. Initial magnetizing transients. Methods of determining reactance, regulation, and short-circuit forces. Three-winding transformers. Mercury arc rectifiers. *Peters.*

EE 166W. Circuit Interruption; 2 credits. Fundamental studies in circuit interruption by an arc. Effects of resistances, inductances, and capacities; calculation of arc energies, switching surges; etc. *Hellmund and Ludwig.*

EE 171W. Electrical Insulation; 2 credits. *Hill.*

EE 172W. Laboratory Technique; 2 credits. *Miner and Tenney.*

EE 181W. Symmetrical Components, I; 2 credits. The application of the principle of symmetrical components to the calculation of currents and voltages in transmission systems when subjected to unbalanced loads and short circuits. The problems used serve to investigate the sequence constants of lines. *Lewis.*

EE 182W. Symmetrical Components, II; 2 credits. A course following *EE 181W*, in which the special method of calculating the performance of machinery when subject to balanced load is developed. The method is applied to transformers, generators, and induction motors.

EE 183W. Slow Transients; 2 credits. Transients in simple circuits of constant resistance, inductance, and capacity leading to the solution of the generalized static network, eddy currents in solid cores, and transients in polyphase machines. *Wagner.*

EE 191W, 192W. Selected Electrical Phenomena; 2 credits. Conduction in gases, kinetic theory of gases, electrons and ions, ionization by collision, sparking potentials, glow discharge, mobilities of ions, thermal ionization, arc discharge, applications to switches and lightning arresters, electronic tubes, etc. *Hoard.*

EE 193W. Conduction in Gases; 2 credits. The course proceeds to the basis of the theory of ionization, a study of ionizing agents, kinetics of ions, mobility, diffusion, recombination, space charges, Langmuir's theory of currents to an electrode, sparkover phenomena Townsend's theory, Paschen's law, and Townsend's law of similitude, glow discharge, and corona. Electric arc theories of cathode, anode, and positive column, stability and extinction of arc are developed. Applications to lightning arresters, circuit breakers, switches and fuses. *Slepian.*

ME 151W. Theory of Elasticity; 2 credits. The elements of vector analysis are considered as an introduction to the analysis of stress and strain and to tensor analysis. Mohr's representation of a tensor; the general equations of the theory of elasticity; St. Venant's theory of the bending and torsion of beams; mathematical theory of flat plates; concentration of stress and of loads; curved shells; etc. *Nadai.*

ME 162W. Applied Elasticity; 2 credits. The application of strength of materials and of the theory of elasticity in calculating stresses and deflections in machine parts, bending, and torsion of thin bars, torsion of shafts, stresses in circular rings, rotating discs and cylinders, the buckling of beams, the bending of flat plates, stress concentration, etc. *Nadai.*

ME 163W. Technical Dynamics; 2 credits. The aspects of statics, kinematics, and dynamics, important to the designer, followed by a discussion of vibration problems in simple mechanical systems. An introduction to advanced dynamics, with applications to balancing of rotating bodies, balancing of reciprocating engines, torsional vibrations, and critical speeds in rotating machinery. *Stone and Soderberg.*

ME 171W. Mechanical Design of Electrical Machinery, I; 2 credits. The application of strength of materials and of applied elasticity in the design and calculation of machine members and parts

ME 172W. Mechanical Design of Electrical Machinery, II; 2 credits. A study of the flow of fluids, the performance of fans, heat flow in solids, heat transfer from solids to fluids, and the storage of heat as applied to the heating and cooling of machines. Derivation of formulas for temperature distribution, heat transfer, and transient heating and cooling curves for special cases. A second portion of the course develops the fundamentals of lubrication in the light of recent discoveries. The hydrodynamical theory of viscous oil films. Conditions of semifluid lubrication. Bearing constructions employed in present-day engineering. Antifriction bearings. *Penney.*

ME 173W. Mechanical Design of Electrical Machinery, III; 2 credits. The principles of the arts appealing to the eye are related to the problems of the industrial designer, through an analytical comparison of industrial products with notable design examples in architecture, furniture, ceramics, and the decorative arts. Supplemented by class work in pencil and clay. *Dohner.*

ME 181W. Electro-Mechanics; 2 credits. The principle of the storage of energy in electric circuits and the theorem of constant linkages are used to derive the fundamental equations for forces between electric circuits. Forces between bus bars, forces in opening switches, pull of magnets, unbalanced radial pull on armatures, normal and transient torque in rotating machines, vibrations produced by alternating or pulsating currents, the effect of unbalanced pull on the vibration of rotating parts, etc. *Ludwig.*

ME 182W. Testing of Materials; 2 credits. Static and dynamic tests of available materials to meet modern service conditions. Application of strength theories in the use of test data for design purposes. Factors involved in the assignment of allowable working stresses. *McVetty.*

IE 161W, 162W. Distribution Engineering; 2 credits. The organization, training, and direction of a technical staff in marketing. Development of potential markets for producers' and consumers' goods of a technical nature. *Lester.*

Met 161W. Physical Metallurgy; 2 credits. Crystal structure of metals and alloys and its relation to physical and mechanical properties. Application of X rays to industry. Interpretation and use of equilibrium diagrams in relation to the heat treatment of alloys. General types of alloys; solid solution, eutectiferous alloys, intermetallic compounds. Effect of plastic deformation and temperature upon physical and mechanical properties of alloys. General theories of hardening of metals and alloys. Alloys used in engineering practice, ferrous and nonferrous. Diseases of metals and alloys. Corrosion and its prevention. *Hensel.*

197W, 198W. Research; various credits. *Staff (resident or nonresident).*

297W, 298W. Seminar; various credits. A discussion of reports on current research in mechanics, mechanical engineering, electrical engineering, physics, mathematics, and metallurgy. *Staff.*

301W, 302W. Thesis; various credits. *Staff.*

Appendix II—Completed Theses

The following list of thesis subjects, together with the name of the candidate, illustrates the wide variety and scope of material covered in the thesis research.

Stresses and Reactions in Expansion Pipe Bands, A. M. Wahl.

Arc Characteristics in an Oil Circuit Breaker, R. C. Van Sickle.

Forced Vibrations With Coulomb Damping, J. P. Den Hartog.

Some Considerations of Air Flow in a Salient Pole Alternator, S. Beckwith.

The Effect of Third Harmonic Heating on 6-Phase Synchronous Converter, I. deVilliers.

A Mathematical Analysis of a Fiction Drive Manufactured by Krupp, M. B. Hogan.

Two Winding A-C Generators for Large Power Systems, L. A. Kilgore.

Eddy Current Losses in the Armature Conductors of D-C Machines and Their Effect on Commutation, H. C. Myers.

Short-Circuit Torque in Synchronous Machines Without Damper Windings, G. W. Penney.

An Investigation of the Fundamental Critical Speeds of Multiple Shafts, J. J. Ryan.

Effect of Phase-to-Ground Fault on Symmetry of Transmission Lines, S. P. Sashoff.

Forces on Turbine Generator Stator Windings During Short Circuits, J. F. Calvert.

Vacuum Tube Voltmeter Design, R. W. Carlisle.

A Study of Improving the Method of Calculating the Reactance Voltage in Distribution Transformers, J. R. Gaston.

The Natural Frequency of Lateral Vibration in the Frames of Electrical Machines, H. E. Hall.

Weight Transfer in Electric Locomotives Caused by the Equalization of Locomotive and the Draw Bar Pull, M. B. Karelitz.

Pressure Phenomena in Oil Circuit Breakers, W. M. Leeds.

The Short Time Temperature Rise of Railway Motor Armatures, D. A. Lightband.

Determination of Stresses in Discs of Conical Profiles, F. C. Rushing.

A Study of the Vibration Motion of a Loaded Flexible Shaft Having a Nonuniform Moment of Inertia During Rotation, B. A. Rose.

Circulating Currents in the Brushes of a D-C Machine, R. M. Baker.

The Characteristics of Inverse Time-Delay Tripping Devices for Small Circuit Breakers, M. W. Brainard.

A Teachable Presentation of Fundamental Principles of Velocity, Acceleration, and Inertia Forces of Machines, P. H. Black.

Characteristics of D-C Arc Motion in Restricted Slots, F. Buck.

An Improved A-C Potentiometer, S. L. Burgwin.

Premature Engagement of Gear Teeth Caused by Tooth Deflection, A. H. Burr.

The Cathode Ray Oscillograph and Its Application to the Investigation of Transient Problems, M. E. Gainder.

An Economic Comparison of Electric Drives for Induced Draft Fans in Large Generating Stations, G. E. Garnhart.

Symmetrical Components in Systems of Symmetrical Phase Coördinates, B. K. Hovey.

An Investigation of Stresses in Sucker Rod Joints, E. N. Kemler.

The Effect of Unsymmetrical Magnetic Fields on the Generation of Ultra-Short Waves in a Magnetically Controlled Vacuum Tube, G. R. Kilgore.

Strength of Nailed Joints of Wood Through Lateral Resistance of the Nails, F. Paulsen.

A Method for Calculating the Bolt Spacing on Transformer Tanks, F. J. Reed.

The Time-Lag of the Oscillograph Vibrator Behind the Applied Force, V. S. Thomander.

The Design and Characteristics of a Current Transformer With Alternating Current Superposed on Direct Current, J. G. Hieber.

A Unique Equipment for Testing Room Conditioners, R. E. Holmes.

The Electrical Characteristics of Synchronous Drive Motors, J. MacBride Kay.

The Graphical Solution of Electrostatic Fields, M. G. Leonard.

Some 2-Dimensional Cases of Discontinuous Distributions of Pressure, C. W. MacGregor.

The Design of a D-C Double Commutator Planer Motor, M. L. Manning.

An Analysis of the Heat Flow in the Thermal Overload Tripping Device for Small Circuit Breakers, J. W. May.

The Development of the Art of Electric Welding as Revealed by Inventions Patented in the United States, W. D. O'Connor.

Saturating Reactances in Electric Circuits, E. L. Harder.

A Study of Class *B* and Class *C* Output Tank Circuits, P. H. Osborn.

Higher Efficiency Fans for Turbine Generators, C. E. Peck.

The Distribution of Stress Due to a Single Force Acting on the Edge of a Circular Hole in an Infinite Plate, W. O. Richmond.

The Bending of Semicircular Plates and Rings With and Without Radial Slots, A. M. Wahl.

Restriking of Low Voltage Alternating Current Welding Arcs With Superposed High Frequency Discharges, F. Blackmore.

Dielectric Recovery of Turbulent A-C Arcs, T. E. Browne, Jr.

The Graduate Student Training Course for Engineers of the Westinghouse Electric and Manufacturing Company, A. M. Dudley.

The Determination of the Proper Size Elevator Motor for Express Service in Rockefeller Center, New York City, W. W. Gregory.

The Characteristics and Applications of the Copper-Oxide Photoelectric Cell, G. W. Hewitt.

Transposition of Conductors in Transformer Windings, H. H. Wagner.

Starting Performance of Salient Pole Synchronous Motors, R. D. Reed.

A Special Type of Double Deck Damper Windings for Synchronous Motors, C. C. Shutt.

Methods of Improving Starting Commutation of Single-Phase Series Railway Motors, R. E. Tobey.

The Design of Long Distance Pipe Lines for Gas, K. C. Ripley.

Air Conditioning Corrections for Subnormal Wall Temperatures, D. A. Taylor.

The General Torsion Problem, M. Stone.

An A-C Potentiometer

A rectangular coördinate potentiometer circuit is described in this paper, the chief features of which are the elimination of the usual phase shifting transformer and the slide-wire type of potentiometer resistor. Although not yet available in commercial form, this potentiometer has been in use in the laboratory for several years with good results, particularly in magnetic measurements at low and medium inductions and in measurements of the power factor of capacitors.

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WHILE the a-c potentiometer may not be adapted as well to a particular test as a more specialized meter or bridge circuit, its chief advantage is that it can be used satisfactorily for a very wide range of measurements. Furthermore, in several particular types of tests such as the measurement of magnetic characteristics of iron cores at low and medium inductions, the a-c potentiometer is the most, if not the only, practical method of obtaining satisfactory results. However, the use of the a-c potentiometer has been restricted greatly, probably because of several practical difficulties which never have been eliminated satisfactorily in spite of the many types of a-c potentiometers that have been developed. No attempt will be made in this paper to discuss these types as a very complete summary and description of them has been published by Drysdale ("Alternating-Current Potentiometers and Their Applications," *Journal* of the Institution of Electrical Engineers, London, March, 1930).

The most satisfactory type of a-c potentiometer from the standpoint of convenience and accuracy of testing generally is conceded to be the rectangular coördinate potentiometer used in conjunction with a phase shifter. However, the various a-c potentiometers of this type that have been developed all have one or more of the following defects:

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1. The phase shifter must be changed when the test frequency is changed. Furthermore, in many measurements where a low power factor is involved, the phase setting of the phase shifter is not sufficiently stable or the shift sufficiently continuous for satisfactory results.
2. In commercial testing the slide-wire potentiometers are not very satisfactory as they require too much attention to keep them in condition.
3. Some types require very frequent checking of the quadrature phase relation between the potentiometers.
4. Leakage and capacitance effects in the types that have the power and detector circuits directly coupled are quite troublesome in some tests.

For making core-loss and permeability measurements at low inductions on small iron cores as has been mentioned, the author found that the a-c potentiometer with all its defects provides the most satisfactory method available. For this reason an attempt has been made to eliminate some of the difficulties mentioned. The attempt has resulted in the development of a circuit that has been used in the laboratory for several years. The main features of this potentiometer are:

1. A single-phase phase shifter which is capable of approximately 150° continuous shift and which maintains a steady phase angle at any setting, provided the frequency remains constant.
2. A method of obtaining the quadrature phase relation between the potentiometers, which is capable of close adjustment and varies only with frequency.
3. The use of variable mutual inductors or variometers for the potentiometers, thus eliminating the contact troubles of the slide-wire potentiometers and at the same time isolating the detector circuits from the power circuit.

This circuit has been in use in the Westinghouse research laboratories for several years with such good results in a wide variety of tests that a portable development model has been built. While a few minor changes are still necessary on this model, tests have shown that it is as capable of accurate results as the laboratory set-up.

The laboratory set-up has been found particularly useful not only in measuring core-loss and permeability of small iron cores, but also in measuring the power factors of capacitors, 2 tests that ordinarily can be made satisfactorily only with very specialized equipment. In connection with such tests it has been found that the accuracy of the results often can be increased greatly by using a mutual inductor in place of the customary resistance shunt for measuring the current.

THE A-C POTENTIOMETER CIRCUIT

The circuit may be divided into 4 main parts each of which will be discussed separately. These divisions, as shown in Fig. 5 in the diagram of the complete circuit, are: (1) the x and y potentiometers; (2) the phase shifter; (3) device for measuring current through the potentiometers; and (4) the null detector for indicating a balance between the potentiometer voltage and the unknown to be measured.

The x and y potentiometers as has been mentioned are 2 variable mutual inductors or variometers, calibrated to read directly in voltage. The connection required to give a quadrature relation between their secondary voltages is shown in Fig. 1, and the vector diagrams of the currents and voltages are given in Fig. 2. The mathematical relations are given in Appendix I. The secondary voltage of M_1 is, of course, in quadrature with the primary current i, while the secondary voltage of M_2 is in quadrature with i_1; but i_1 is in quadrature with i, and therefore the secondary voltage of M_2 is in phase with i and in quadrature with the secondary voltage of M_1.

Quadrature relation between i and i_1, Fig. 1, is obtained by adjusting R_3 and R_4. These values of resistance are different for each frequency and have to be changed when the frequency is changed, but for any given frequency they may be adjusted very closely. The variometers are so constructed that rotating the primary gives a continuous variation of secondary voltage from a negative maximum to a positive maximum. When operating on different frequencies it is necessary to change the value of primary current to maintain the same voltage calibration for the potentiometers.

The circuit for the phase shifter is shown in Fig. 3. Its function is to change the phase angle between the voltage E and the current i to any value over a range of at least 90° for a given value of reactance X and resistance R in the rest of the potentiometer circuit. This variation must be accomplished without changing the value of i. The vector diagrams for the voltages and currents are shown in Fig. 4 and the mathematical relations are given in Appendix II. The shift in phase is obtained by varying R_L, and for the conditions existing in the a-c potentiometer, covers a range of about 150° which is more than sufficient. A disadvantage of this phase shifting method is that it is not independent of frequency; and if it is to be used at more than one frequency, provision must be made for changing the value of the capacitance. The same effect

Fig. 1. Variometer circuit

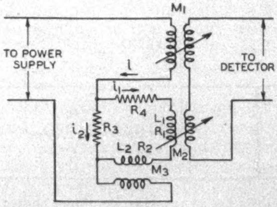
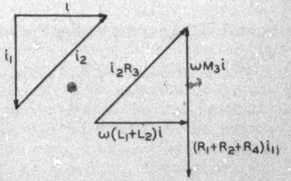


Fig. 2. Vector diagrams for variometer circuit of Fig. 1



could be accomplished by changing the value of the inductance, but for this application where the rest of the circuit is inductive it is more desirable to change the capacitance and keep the inductance constant.

A current measuring device, or perhaps it should be called a voltage measuring device, is necessary to indicate when the voltage of the potentiometers is at the calibrated value. If an ammeter is used to measure the current in the primary circuit, the reading will be different for each frequency. This is a source of inconvenience and possible inaccuracy in tests where it is not necessary to know the frequency accurately. For this reason this potentiometer makes use of a fixed mutual inductor with a high resistance voltmeter connected across the secondary. Thus a voltage is measured that has the same characteristics as the voltage across the potentiometers, and consequently it should be the same for all frequencies. Practically, this is not quite true since in general, the resistance of the voltmeter will not be sufficiently high at the higher frequencies to make the effect of the reactance of the secondary winding negligible; therefore, the voltmeter must be calibrated for the readings at the various frequencies. This variation with frequency is small enough so that the calibrated voltage of the potentiometer can be obtained quite accurately although the actual frequency may deviate several per cent from the value assumed. The circuit for such a current measuring device is shown in Fig. 5 and will be discussed in detail later in this paper.

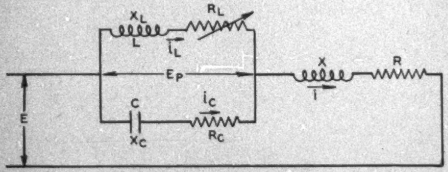


Fig. 3. Phase shifter circuit

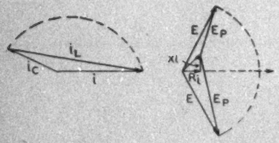


Fig. 4. Vector diagrams for phase shifter circuit of Fig. 3

For a null-current detector it is desirable to have a device that is very sensitive at the fundamental test frequency and insensitive to all other frequencies, yet it should be capable of operating at various fundamental frequencies. These 2 characteristics are contradictory and consequently both cannot be obtained without making some change in the detector when the operating frequency is changed. The most satisfactory detector for frequencies up to 300 cycles per second has been found to be the tuned vibration galvanometer of the moving coil type with interchangeable elements for the different frequencies. For frequencies above 300 cycles the low impedance telephone receiver is most satisfactory, although the higher harmonics may necessitate an additional filter circuit in some cases. These 2 detectors have the advantage of simplicity in comparison with most other detector arrangements, and at the same time are sufficiently rugged and sensitive to obtain accurate results in commercial service.

CONSTRUCTION OF A PORTABLE A-C POTENTIOMETER

The complete circuit for this potentiometer is shown in Fig. 5. The instrument is designed to operate on 110 volts and is capable of operation on 9 different frequencies ranging from 25 to 1,000 cycles per second. The potentiometers have 2 ranges, from 0 to 5, and from 0 to 50 millivolts.

The potentiometer can be divided into 4 main parts as shown in Fig. 5. The construction of each of these divisions will be discussed separately and then the assembly in one instrument.

Variable Inductor Potentiometers. In the laboratory set-up, Brooks' inductors were used satisfactorily, but for a portable instrument they are too large so that 2 inductors of the variometer type were designed. To make these variometers more nearly static than the usual type, each consists actually of 2 variometers, mounted one above the other with the moving coils on the same shaft, and with the windings connected so that voltage induced by a stray field in one tends to balance out the voltage induced in the other. The windings are of Litzendraht wire supported upon micarta forms. As little metal as possible is used in the construction in order to minimize eddy currents. The maximum mutual inductance obtainable with either of these variometers is approximately 2.5 mh using the main secondary winding, and $^1/_{10}$ of that value using a smaller secondary winding.

These 2 secondary windings are wound upon the stator instead of the rotor so that any induced voltages from stray fields vary the calibration by a constant amount, and correction can be made by taking a zero balance. The primary windings are of somewhat larger Litzendraht wire as it is desirable to keep the resistance as low as possible.

The iron core mutual inductor of the phase splitting arrangement is designed with a 2 to 1 ratio of primary to secondary turns so that the mutual inductance is approximately twice the self-inductance of the secondary. As it is desirable to keep the resistance of the secondary small, it is wound next to the core. The core is of 5-mil "hipernik" (a specially heat treated alloy of iron and nickel) E-punchings, with the legs cut in such a way that an air gap may be placed in the center leg and the other 2 legs lapped. This is done to get fairly constant inductance and a good ratio of reactance to resistance without causing too much external magnetic field.

The 2 resistors included in the phase splitting arrangement are removable, as different values of resistance are required for each frequency. Therefore, the 2 resistors for each frequency are wound noninductively upon a card, and are arranged to fit 3 binding posts provided on the control panel of the instrument.

Phase Shifter. The phase shifter circuit shown in Figs. 3 and 5, differ in that a transformer with a capacitor across its secondary is substituted in Fig. 5 for X_c and R_c as shown in Fig. 3. The 2 circuits are equivalent electrically, but the transformer circuit has a considerable advantage for this application because the equivalent capacitance in the primary circuit can be varied by changing the transformer ratio. Furthermore, for low frequencies where large capacitance is required, the size of the phase shifter can be reduced, as a large capacitance may be obtained with a small capacitor by using the proper transformer ratio. Equivalent resistances, approximately equal to the necessary values of R_c over the frequency range from 25 to 1,000 cycles per second, also can be obtained by properly designing the transformer. Such a transformer was designed and built for use with a 1-μf capacitor. The core is made of 5-mil "hipernik" E-punchings, lapped in the usual way. The induction in the core and the resistance of the windings are such as to give approximately the correct values of R_c for each frequency; 8 taps are placed in the secondary winding to give the correct equivalent capacitances for the 9 desired frequencies.

The inductance L, Fig. 3, is obtained by means of an iron core inductor, having a core similar to the one used in the phase splitting arrangement for the potentiometer variometers. The exact value of inductance is obtained by adjusting the air gap with the phase shifter in operation so that there is no change in current for a wide variation of the phase shifter rheostat. The inductance necessary for this condition is approximately 2.5 h.

The phase shifter rheostat is designed to give variations from 0 to 20,000 ohms and is capable of carrying 0.25 amp in the lower resistance ranges. This range is obtained by using 3 wire-wound rheostats in series, thus giving very fine adjustment at all resistances. The rheostats are of the circular sliding-arm type and have the following ratings: (1) 0–20 ohms, 12.5 watts; (2) 0–1,800 ohms, 150 watts; (3) 0–20,000 ohms, 150 watts. To keep the size within reasonable limits the third rheostat is constructed so that the first step is 1,800 ohms.

Current Measuring Device. As has been mentioned previously, the purpose of this device is to indicate the value of current necessary to give the calibrated voltage on the potentiometer. The device, as shown in Fig. 5, consists of an iron core mutual inductor, a thermocouple, and a microammeter. The core of the mutual inductor is made of 5-mil "hipernik" E-punchings which are stacked to give an air gap sufficient to keep the inductance practically constant for small changes in current. The value of mutual inductance is 20 mh, and the self-inductance of the secondary 6.36 mh. The thermocouple is similar to those used in Rawson "multimeters" and is capable of carrying a current of 10 ma. A Westinghouse d-c 200-μa microammeter is used to indicate the thermocouple current. The scale of the microammeter is calibrated in cycles to indicate the correct current at each frequency.

Detector. The low frequency detector, as shown in Fig. 5, is a vibration galvanometer of the type manufactured by H. Tinsley and Company, having replaceable elements tuned to the various desired frequencies. A variable rheostat is shunted across the galvanometer to give variation in sensitivity. As may be seen in Fig. 5, 2 binding posts are placed in the secondary circuit of the variable inductor potentiometers to which any type of detector desired, may be connected. At audio frequencies it is usually desirable to use a low impedance telephone receiver, although in some cases high impedance headphones may be preferable.

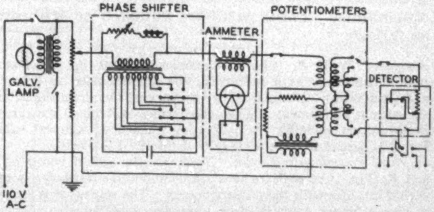


Fig. 5. Complete circuit of the a-c potentiometer described in this paper

The Assembly. All component parts of this a-c potentiometer are mounted in one box which, with the cover, measures 22$^1/_2$ in. long, 16$^1/_2$ in. wide, and 11$^1/_2$ in. deep. The total weight is approximately 55 lb.

No attempt is made to shield the potentiometer electrostatically because of the difficulty involved, and because in general either the external capacitance and leakage effects are negligible or easily can be made negligible. The component parts do not require mutual shielding since the constants of the circuit are such as to make capacitance or leakage effects inappreciable over the frequency range for which the potentiometer is designed. It is necessary, however, to eliminate mutual inductance effects between component parts and to provide a means for correcting for the effect of external magnetic fields. The first is accomplished, as has been explained previously, by special design of the inductors, both air and iron core, and also by mounting them as far apart as possible. Correction for external magnetic fields by taking a zero reading also has been explained. In addition to these precautions, it is necessary to keep all metal parts far enough from the variometers to make the eddy currents negligible. Mutual inductance between the variometers is kept low, although it would cause no error since the variometers are calibrated after being mounted in the potentiometer box.

To make the potentiometer as nearly self-contained as possible, several additional pieces of apparatus are included, as shown in Fig. 5. These are: a

110/6-volt transformer for the galvanometer lamp; a 250-ohm rheostat across the power supply to vary the current; and a selector switch in the detector circuit to permit an easy change from one unknown voltage to another.

CALIBRATION

While it is possible to calculate and set accurately the values of resistance and inductance of the several parts of the potentiometer before assembling, it was found more practical to set these values approximately and make the final adjustments after assembling. These parts are adjusted or calibrated as follows:

Ammeter. With R_4 (Fig. 1) disconnected and the quadrature potentiometer set at a maximum, the potentiometer is balanced against a known voltage of 50 mv by varying the phase shifter and the current adjustment. When the balance is obtained the current is the correct value for the calibrating frequency. Current values for other desired frequencies may be determined similarly.

In-Phase Potentiometer Circuit. To obtain the correct values of R_3 and R_4 (Fig. 1) at each frequency a noninductive resistance is connected in series with the potentiometers. The resistance is such as to give a 50-mv potential drop when the potentiometer ammeter indicates the correct value of current for the calibrating frequency. The potentiometer is balanced against the voltage drop across this resistance by varying R_3 and R_4 with the in-phase potentiometer set at the maximum value and the quadrature potentiometer at zero. When the detector indicates a balance, R_3 and R_4 are the correct values for the calibrating frequency.

Phase-Shifter Inductor. The air gap of the phase-shifter inductor X_L (Fig. 3) is adjusted by varying the gap until the potentiometer ammeter reads the same for the zero and maximum positions of the phase-shifter rheostat.

USE OF THE A-C POTENTIOMETER

Perhaps it may serve to clarify the ideas of those unfamiliar with potentiometer measurements to show how the a-c potentiometer is used in making actual tests. Furthermore, in most a-c tests, it is assumed that the voltages both known and unknown vary sinusoidally. Since this is not generally true, the validity of the assumption must be investigated. For this purpose 2 representative tests will be discussed, the measurement of the losses and permeability of an iron core, and the measurement of the power factor of a capacitor.

Measurement of Core Loss and Permeability of Iron Cores. It is assumed that in this test the power in watts and the reactive power are to be measured for given inductions in the core. The circuit most generally used, is shown in Fig. 6. (See "Some Applications of the A-C Potentiometer," by T. Spooner, *Journal* of the Optical Society of America and *Review of Scientific Instruments*, v. 12, March 1926.) Rheostat P serves to vary the current I flowing through the primary winding of the iron core S and also shunt R. The secondary winding, of N_2 turns, gives the voltage E which is reduced to the range of the a-c potentiometer by the voltage divider. The potentiometer is connected as shown, a selector switch in the potentiometer making it possible to connect the potentiometer to either the voltage divider or the current shunt. The vector diagram of Fig. 6 shows the relations of the quantities necessary to measure the watts and reactive power for any given induction in the iron.

A source of error particularly in testing iron cores is nonsinusoidal voltages. The power supply voltage is generally quite free of harmonics or can be made so. Thus the potentiometer voltage can be made nearly sinusoidal. However, even assuming a sinusoidal supply voltage, the harmonics have not been eliminated from the circuit of the sample; for if a sinusoidal voltage be impressed upon an iron core inductor, the exciting current will not be sinusoidal. Consequently, if the exciting circuit of the iron core contains impedance, neither the voltage impressed on the sample nor the exciting current will be sinusoidal. Under these conditions the results obtained by the a-c potentiometer are in error, as only the fundamentals of the voltage waves are measured. At low inductions when the harmonics are relatively small, this error can be neglected; but for higher inductions the impedance of the exciting circuit must be kept small since this allows the voltage impressed upon the sample to be more nearly sinusoidal, and the potentiometer gives more nearly correct results. To make the error negligible, it is necessary only to make the impedance of the exciting circuit sufficiently small. In the circuit of Fig. 6, this can be accomplished by making the current through resistor P large in proportion to the exciting current, and by reducing the impedance of the primary circuit; the latter may be done by replacing shunt R with a mutual inductor having only a few turns in the primary and many turns in the secondary. With such an arrangement the effect of the harmonics can be made negligible at inductions less than 12,000 gausses. It may be pointed out here that the use of such a mutual inductor also will give more accurate results than a resistance shunt for most measurements where the power factor is less than 0.70, although this has nothing to do with harmonics.

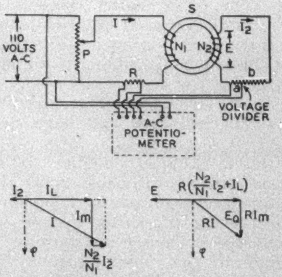


Fig. 6. Circuit for measuring core loss and permeability of iron cores, and associated vector diagrams

A general rule, derived from what has been said in the preceding paragraphs, might be stated "Correct measurements of power or any quantity involving the scalar product of 2 voltages can be made by the a-c potentiometer, only when at least one of the voltages is sinusoidal."

Measurement of the Power Factor of a Capacitor. Because of the low power factor of most capacitors, it is rather difficult to measure their losses accurately with wattmeters or other simple means. However, it is possible to obtain very accurate results with the a-c potentiometer. The circuit that in general gives the best results is shown in Fig. 7. Rheostat P serves to adjust the current I flowing through the capacitor C the power factor of which is to be measured. Inductance L is made to form a series resonant circuit with C, to reduce harmonics in the voltage across the capacitor and to provide an easy and safe means of obtaining capacitor voltages higher than the supply voltage. The voltages to be measured by the a-c potentiometer are: (1) the voltage induced in the secondary of the mutual inductance M, which is proportional to and in quadrature with I; and (2) the voltage across resistance a of the voltage divider, which is in phase with and proportional to E.

From the vector diagram in Fig. 7 it is apparent that the ratio of the 2 components, E_p and E_q, of MI give the tangent of the angle between E and I. Therefore E_q/E_p can be taken as the power factor since the cotangent is almost equal to the cosine for angles close to 90°.

Several precautions must be observed in making measurements on capacitors with low power factors:

1. The mutual inductance M must be unaffected by stray magnetic fields and must have an exact quadrature phase relation between the primary current and the secondary voltage; this means that an astatic air core mutual inductance, free from eddy currents, must be used.
2. The voltage measured on the voltage divider must be exactly in phase with E.
3. Stray magnetic fields in the potentiometer must be eliminated or corrected by a zero balance.

Harmonics are not as serious in this case as in the previous example, since a sinusoidal supply voltage will give accurate results in capacitor measurements. Furthermore, even if the supply should contain harmonics, the series resonant circuit will reduce them to a much smaller value in the test capacitor, and if desired a series resonant circuit may be used in the power supply of the potentiometer.

Appendix I—Calculation of Phase Splitter Circuit Constants

The circuit constants of Fig. 1 may be evaluated from the geometry of the vector diagram shown in Fig. 2. However, it is just as simple to calculate them in the usual way. Referring to Fig. 1, it is desired to make i and i_1 equal in value, but with a quadrature phase relation, that is:

$$\frac{i}{i_1} = j \tag{1}$$

The network gives 2 equations:

$$i_1 + i_2 = i \tag{2}$$

$$R_3 i_2 = [R_1 + R_2 + R_4 + j\omega(L_1 + L_2)]i_1 + j\omega M_3 i \tag{3}$$

Eliminating i, i_1, and i_2 from eqs 1, 2, and 3 gives the following:

$$\omega M_3 = R_1 + R_2 + R_3 + R_4 \tag{4}$$

$$R_3 = \omega(L_1 + L_2) \tag{5}$$

Equations 4 and 5 express the relations between the circuit constants necessary to give the desired relations between i and i_1.

If an iron core inductance M_3 is used, eq 4 remains the same but eq 5 becomes

$$R_3 - r = \omega(L_1 + L_2) \tag{5a}$$

where r is an apparent resistance due to losses in the iron core.

Appendix II—Calculations of Circuit Constants for Phase Shifter

Referring to the circuit diagram Fig. 3, X and R are respectively the equivalent reactance and resistance of the entire potentiometer circuit outside of the phase shifter. It is desired in this case to make the absolute value of the current constant for all values of R_L. Thus it follows that the total impedance Z of the circuit must be a constant, independent of R_L. To find the values of X_c, R_c, and X_L necessary to accomplish this, it is necessary to expand the equation for the absolute value of impedance of the circuit shown in Fig. 3, in powers of R_L thus:

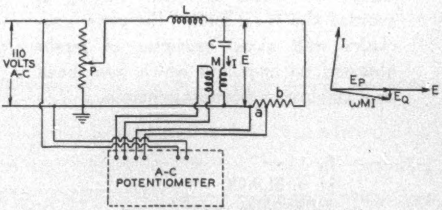


Fig. 7. Circuit for measuring power factor of capacitors, and associated vector diagram

$$AR_L^2 + BR_L + C = 0$$

where A, B, and C are functions of the circuit constants except R_L.

Since this equation must be true for all values of R_L, each of these coefficients must be equal to zero. These operations result in the following equations:

$$A = (R_c^2 + X_c^2) + 2(RR_c - XX_c) + R^2 + X^2 - Z^2 = 0 \tag{6}$$

$$B = -2R_c(Z^2 - R^2 - X^2) + 2R(R_c^2 + X_c^2) = 0 \tag{7}$$

$$C = -(R_c^2 + X_c^2 - 2X_LX_c)(Z^2 - R^2 - X^2) + 2XX_L(R_c^2 + X_c^2) = 0 \tag{8}$$

From the simultaneous eqs 6, 7, and 8 the values of R_c, X_c, and X_L may be obtained in terms of Z, X, and R.

$$X_c = \frac{(Z^2 - X^2 - R^2)(Z - X)}{R^2 + (Z - X)^2} \tag{9}$$

$$R_c = \frac{(Z^2 - X^2 - R^2)R}{R^2 + (Z - X)^2} \tag{10}$$

$$X_L = \frac{(Z^2 - X^2 - R^2)}{2Z} \tag{11}$$

The maximum possible phase shift, $\Delta\theta$, that can be obtained, is given by the following expression:

$$\Delta\theta = -\text{arc tan}\, \frac{\dfrac{X_L(R_c^2 + X_c^2) - X_c(R_L^2 + X_L^2)}{(R_c + R_L)^2 + (X_L - X_c)^2} + X}{\dfrac{R_c(R_L^2 + X_L^2) + R_L(R_c^2 + X_c^2)}{(R_c + R_L)^2 + (X_L - X_c)^2} + R} \left|\begin{matrix} R_L = \infty \\ \\ R_L = R_0 \end{matrix}\right. \tag{12}$$

If X and R are assumed negligible the expression becomes:

$$\Delta\theta = \text{arc tan}\, \frac{X_c}{R_c} + \text{arc tan}\, \frac{X_L(R_c^2 + X_c^2) - X_c(R_0^2 + X_L^2)}{R_c(R_0^2 + X_L^2) + R_0(X_L - X_c)^2}$$

Stabilized Feed-Back Amplifiers

This paper describes and explains the theory of the feed-back principle and demonstrates how stability of amplification, reduction of modulation products, and certain other advantages follow when stabilized feed-back is applied to an amplifier. The underlying principle of design by means of which "singing" is avoided also is set forth. The paper concludes with some examples of results obtained on amplifiers which have been built employing this new principle.

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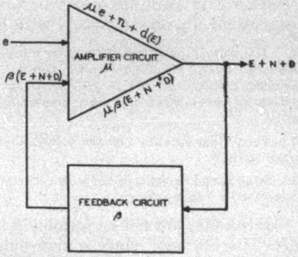
DUE TO ADVANCES in vacuum-tube development and amplifier technique, it now is possible to secure any desired amplification of the electrical waves used in the communication field. When many amplifiers are worked in tandem, however, it becomes difficult to keep the over-all circuit efficiency constant, variations in battery potentials and currents, small when considered individually, adding up to produce serious transmission changes for the over-all circuit. Furthermore, although it has remarkably linear properties, when the modern vacuum tube amplifier is used to handle a number of carrier telephone channels, extraneous frequencies are generated which cause interference between the channels. To keep this interference within proper bounds involves serious sacrifice of effective amplifier capacity or the use of a push-pull arrangement which, while giving some increase in capacity, adds to maintenance difficulty.

However, by building an amplifier whose gain is made deliberately, say 40 decibels higher than necessary (10,000 fold excess on energy basis) and then feeding the output back to the input in such a way as to throw away the excess gain, it has been found possible to effect extraordinary improvement in constancy of amplification and freedom from nonlinearity. By employing this feed-back principle, amplifiers have been built and used whose gain varied less than 0.01 db with a change in plate voltage from 240 to 260 volts and whose modulation products were 75 db below the signal output at full load. For an amplifier of conventional design and comparable size this change in plate voltage would have produced about 0.7 db variation while the modulation products would have been only 35 db down; in other words, 40 db reduction in modulation products was effected. (On an energy basis the reduction was 10,000 fold.)

Stabilized feed-back possesses other advantages including reduced delay and delay distortion, reduced noise disturbance from the power supply circuits and various other features best appreciated by practical designers of amplifiers.

It is far from a simple proposition to employ feed-back in this way because of the very special control required of phase shifts in the amplifier and feed-back circuits, not only throughout the useful frequency band but for a wide range of frequencies above and below this band. Unless these relations are maintained, singing will occur, usually at frequencies outside the useful range. Once having achieved a design, however, in which proper phase relations are secured, experience has demonstrated that the performance obtained is perfectly reliable.

Fig. 1. Amplifier system with feed-back



e. signal input voltage
μ. propagation of amplifier circuit
μe. signal output voltage without feed-back
n. noise output voltage without feed-back
d(E). distortion output voltage without feed-back
β. propagation of feed-back circuit
E. signal output voltage with feed-back
N. noise output voltage with feed-back
D. distortion output voltage with feed-back

The output voltage with feed-back is $E + N + D$ and is the sum of $\mu e + n + d(E)$, the value without feed-back plus $\mu\beta[E + N + D]$ due to feed-back.

$$E + N + D = \mu e + n + d(E) + \mu\beta[E + N + D]$$

$$[E + N + D](1 - \mu\beta) = \mu e + n + d(E)$$

$$E + N + D = \frac{\mu e}{1 - \mu\beta} + \frac{n}{1 - \mu\beta} + \frac{d(E)}{1 - \mu\beta}$$

If $|u\beta| \gg 1$, $E \doteq = \frac{e}{\beta}$. Under this condition the amplification is independent of μ but does depend upon β. Consequently the over-all characteristic will be controlled by the feed-back circuit which may include equalizers or other corrective networks.

The carrier-in-cable system dealt with in a recent Institute paper (Carrier in Cables by A. B. Clark and B. W. Kendall. A.I.E.E. TRANS., Dec. 1933, p. 1050) involves many amplifiers in tandem with many telephone channels passing through each

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Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. winter convention, Jan. 23–26, 1934. Manuscript submitted March 28, 1933; released for publication December 4, 1933. *Not published in pamphlet form.*

amplifier and constitutes, therefore, an ideal field for application of this feed-back principle. A field trial of this system was made at Morristown, New Jersey, in which 70 of these amplifiers were operated in tandem. The results of this trial were highly satisfactory and demonstrated conclusively the correctness of the theory and the practicability of its commercial application.

CIRCUIT ARRANGEMENT

In the amplifier of Fig. 1, a portion of the output is returned to the input to produce feed-back action. The upper branch, called the μ circuit, is represented as containing active elements such as an amplifier while the lower branch, called the β-circuit, is shown as a passive network. The way a voltage is modified after once traversing each circuit is denoted μ and β, respectively, and the product, $\mu\beta$, represents how a voltage is modified after making a single journey around amplifier and feed-back circuits. Both μ and β are complex quantities, functions of frequency, and in the generalized concept either or both may be greater or less in absolute value than unity: (μ is not used in the sense that it is used sometimes, namely, to denote the amplification constant of a particular tube, but as the complex ratio of the output to the input voltage of the amplifier circuit).

Fig. 2 shows an arrangement convenient for some purposes where, by using balanced bridges in the input and output circuits, interaction between the circuits that connect to the input and output is avoided. Thereby feed-back action and amplifier impedances are made independent of the properties of circuits connected to the amplifier.

GENERAL EQUATION

In Fig. 1, β is zero without feed-back and a signal voltage, e_0, applied to the input of the μ-circuit produces an output voltage. This is made up of what is wanted, the amplified signal, E_0, and components that are not wanted, namely, noise and distortion designated N_0 and D_0 and assumed to be generated within the amplifier. It is further assumed that the noise is independent of the signal and the distortion of modulation a function *only of the signal output*. Using the notation of Fig. 1, the output without feed-back may be written as:

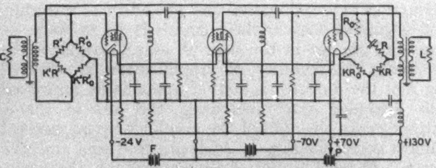


Fig. 2. Circuit of a negative feed-back amplifier

$$E_0 + N_0 + D_0 = \mu e_0 + n + d(E_0) \tag{1}$$

where zero subscripts refer to conditions without feed-back.

With feed-back, β is not zero and the input to the μ-circuit becomes $e_0 + \beta\ (E + N + D)$. The output is $E + N + D$ and is equal to $\mu[e_0 + \beta\ (E + N + D)] + n + dE$ or

$$E + N + D = \frac{\mu e_0}{1 - \mu\beta} + \frac{n}{1 - \mu\beta} + \frac{d(E)}{1 - \mu\beta} \tag{2}$$

In the output signal, noise and modulation are divided by $(1 - \mu\beta)$, and assuming $|1 - \mu\beta| > 1$, all are reduced.

CHANGE IN GAIN DUE TO FEED-BACK

From eq 2, the amplification with feed-back equals the amplification without feed-back divided by $(1 - \mu\beta)$. The effect of adding feed-back, therefore, usually is to change the gain of the amplifier and this change will be expressed as

$$G_{CF} = 20 \log_{10} \left|\frac{1}{1 - \mu\beta}\right| \tag{3}$$

where G_{CF} is *db change in gain due to feed-back.* As a quantitative measure of the effect of feed-back $\frac{1}{1 - \mu\beta}$ will be used and the feed-back referred to as *positive feed-back* or *negative feed-back* according as the absolute value of $\frac{1}{1 - \mu\beta}$ is greater or less than unity. Positive feed-back increases the gain of the amplifier; negative feed-back reduces it. The term feed-back is not limited merely to those cases where the absolute value of $\frac{1}{1 - \mu\beta}$ is other than unity.

From $\mu\beta = |\mu\beta|\,\underline{|\Phi}$ and (3), it may be shown that

$$10^{-\frac{G_{CF}}{10}} = 1 - 2|\mu\beta|\cos\Phi + |\mu\beta|^2 \tag{4}$$

which is the equation for a family of concentric circles of radius $10^{-\frac{G_{CF}}{10}}$ about the point 1, 0. Fig. 3 is a polar diagram of the vector field of $\mu\beta = |\mu\beta|\,\underline{|\Phi}$. Using rectangular instead of polar coördinates, Fig. 4 corresponds to Fig. 3 and may be regarded as a diagram of the field of $\mu\beta$ where the parameter is db change in gain due to feed-back. From these diagrams all of the essential properties of feed-back action can be obtained such as change in amplification, effect on linearity, change in stability due to variations in various parts of the system, reduction of noise, etc. Certain significant boundaries have been designated similarly on both figures.

For example, boundary A is the locus of zero change in gain due to feed-back. Along this parametric contour line where the absolute magnitude of amplification is not changed by feed-back action, values of $|\mu\beta|$ range from zero to 2 and the phase shift, Φ around the amplifier and feed-back circuits equal $\cos^{-1}\frac{|\mu\beta|}{2}$ and, therefore, lies between -90 deg and $+90$ deg. For all conditions inside or above this boundary, the gain with feed-back is increased; outside or below, the gain is decreased.

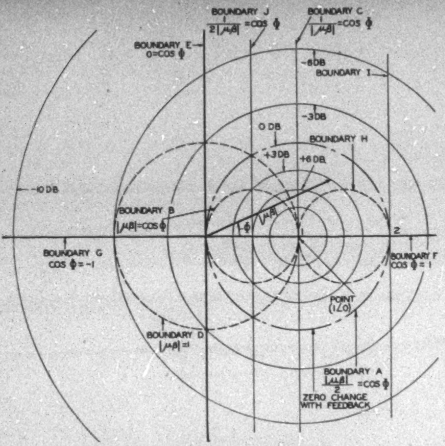


Fig. 3. The vector field of $\mu\beta$

See caption for Fig. 4

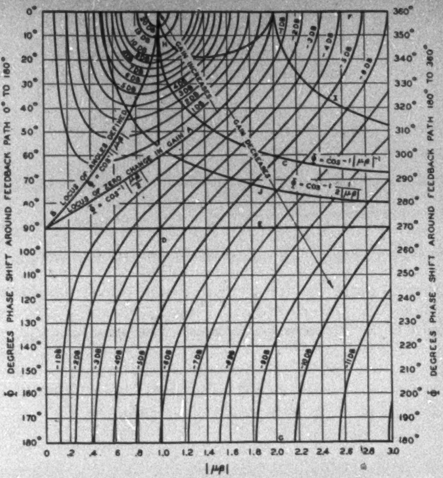


Fig. 4. Phase shift around the feed-back path plotted as a function of $|\mu\beta|$, absolute value of $\mu\beta$

The complex quantity $\mu\beta$ represents the ratio by which the amplifier and feed-back (or more generally μ and β) modify a voltage in a single trip around the closed path

First, there is a set of boundary curves indicated by letters which give either limiting or significant values of $|\mu\beta|$ and ϕ.

Second, there is a family of curves in which db change in gain due to feed-back is the parameter.

Boundaries

A. Conditions in which gain and modulation are unaffected by feed-back.

B. Constant amplification ratio against small variations in $|\beta|$.

Constant change in gain, $\frac{1}{|1-\mu\beta|}$, against variations in $|\mu|$ and $|\beta|$. Stable phase shift through the amplifier against variation in $\Phi\beta$.

The boundary on which the stability of amplification is unaffected by feed-back.

C. Constant amplification ratio against small variations in $|\mu|$.

Constant phase shift through amplifier against variations in $\Phi\mu$.

The absolute magnitude of the voltage fed back $\frac{|\mu\beta|}{|1-\mu\beta|}$ is constant against variations in $|\mu|$ and $|\beta|$.

D. $|\mu\beta| = 1$

E. $\Phi = 90°$. Improvement in gain stability corresponds to twice db reduction in gain.

F.
G. $\left\{\begin{array}{l}\text{Constant amplification ratio against variations in } \Phi. \\ \text{Constant phase shift through the amplifier against} \\ \text{variations in } |\mu| \text{ and } |\beta|.\end{array}\right.$

H. Same properties as β

I. Same properties as E

J. Conditions in which $\frac{|\mu|}{|1-\mu\beta|} = \frac{-1}{|\beta|}$ the over-all gain is the exact negative inverse of the transmission through the β-circuit.

STABILITY

From eq 2, $\frac{\mu e_0}{1-\mu\beta}$ is the amplified signal with feed-back and $\frac{\mu}{1-\mu\beta}$, therefore, is an index of the amplification. It is of course a complex ratio. It will be designated A_F and referred to as the amplification with feed-back.

To consider the effect of feed-back upon stability of amplification, the stability will be viewed as the ratio of a change, δA_F, to A_F where δA_F is due to a change either in μ or β and the effects may be derived by assuming the variations are small.

$$A_F = \frac{\mu}{1-\mu\beta} \tag{5}$$

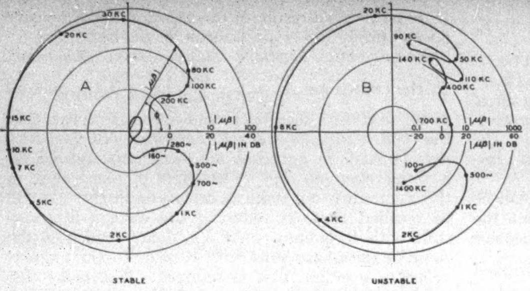
$$\left[\frac{\delta A_F}{A_F}\right]_\mu \doteq \frac{\left[\frac{\delta\mu}{\mu}\right]}{1-\mu\beta} \tag{6}$$

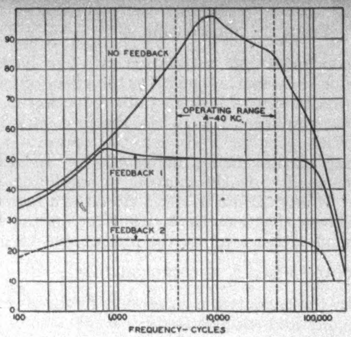
$$\left[\frac{\delta A_F}{A_F}\right]_\beta \doteq \frac{\mu\beta}{1-\mu\beta}\left[\frac{\delta\beta}{\beta}\right] \tag{7}$$

If $\mu\beta \gg 1$, it is seen that μ or the μ-circuit is stabilized by an amount corresponding to the reduction in amplification and the effect of introducing a gain or loss in the μ-circuit is to produce no material change in the over-all amplification of the system; the stability of amplification as affected by β or the β-circuit is neither appreciably improved nor degraded since increasing the loss in the β-circuit raises the gain of the amplifier by an amount almost corresponding to the loss introduced and *vice versa*. If both μ and β are varied and the variations sufficiently small, the effect is the same as if each were changed separately and the two results then combined.

In certain practical applications of amplifiers it is the change in gain or ammeter or voltmeter reading at the output that is a measure of the stability rather than the complex ratio previously treated. The conditions surrounding gain stability may be examined by considering the absolute value of A_F. This is shown as follows:

Let (db) represent the gain in decibels corresponding to A_F. Then





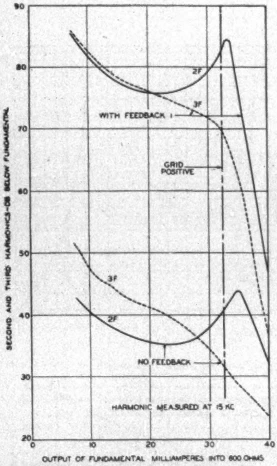


Fig. 5 (above). Measured $\mu\beta$ characteristics of 2 amplifiers

Fig. 6 (above right). Gain-frequency characteristics with and without feed-back of amplifier of Fig. 2

Fig. 7 (left). Modulation characteristics with and without feed-back for the amplifier of Fig. 2

$$(db) = 20 \log_{10} |A_F|$$

$$\delta(db) \doteq 8.686 \left[\frac{\delta |A_F|}{|A_F|}\right] \tag{8}$$

To get the absolute value of the amplification:

$$\mu\beta = |\mu\beta| \underline{|\Phi} \tag{9}$$

$$|A_F| = \frac{|\mu|}{\sqrt{1 - 2|\mu\beta| \cos \Phi + |\mu\beta|^2}} \tag{10}$$

The stability of amplification which is proportional to the gain stability is given by

$$\left[\frac{\delta |A_F|}{|A_F|}\right]_{|\mu|} \doteq \frac{1 - |\mu\beta| \cos \Phi}{|1 - \mu\beta|^2} \left[\frac{\delta |\mu|}{|\mu|}\right] \tag{11}$$

$$\left[\frac{\delta |A_F|}{|A_F|}\right]_{|\beta|} \doteq \left|\frac{\mu\beta}{1 - \mu\beta}\right| \left[\frac{\cos \Phi - |\mu\beta|}{|1 - \mu\beta|}\right] \left[\frac{\delta |\beta|}{|\beta|}\right] \tag{12}$$

$$\left[\frac{\delta |A_F|}{|A_F|}\right]_{\Phi} \doteq -\left|\frac{\mu\beta}{1 - \mu\beta}\right| \left[\frac{\sin \Phi}{|1 - \mu\beta|}\right] [\delta\Phi] \tag{13}$$

A curious fact to be noted from eq 11 is that it is possible to choose a value of $\mu\beta$ (namely, $|\mu\beta| = \sec \Phi$) so that the numerator of the right hand term vanishes. This means that the gain stability is perfect, assuming differential variations in $|\mu|$. Referring to Figs. 3 and 4, contour C is the locus of $|\mu\beta| = \sec \Phi$ and it includes all amplifiers whose gain is unaffected by small variations in $|\mu|$. In this way it is possible even to stabilize an amplifier whose feed-back is positive, i. e., feed-back may be utilized to raise the gain of an amplifier and, at the same time, the gain stability with feed-back *need* not be degraded but on the contrary may be improved. If a similar procedure is followed with an amplifier whose feed-back is negative, the gain stability theoretically will be perfect and independent of the reductions in gain due to feed-back. Over too wide a frequency band practical difficulties will limit the improvements possible by these methods.

With negative feed-back, gain stability always is improved by an amount at least as great as corresponds to the reduction in gain and generally more; with positive feed-back, gain stability never is degraded by more than would correspond to the increase in gain and under appropriate conditions, assuming the variations are not too great is as good or much better than without feed-back. With positive feed-back, the variations in μ or β must not be permitted to become sufficiently great as to cause the amplifier to sing or give rise to instability as defined in the section devoted to the conditions for avoiding singing.

MODULATION

To determine the effect of feed-back action upon modulation produced in the amplifier circuit, it is convenient to assume that the output of undistorted signal is made the same with and without feed-back and that a comparison then is made of the difference in modulation with and without feed-back. Therefore, with feed-back, the input is changed to $e = e_0 (1 - \mu\beta)$ and, referring to eq 2, the output voltage is μe_0 and the generated modulation, $d(E)$, assumes its value without feed-back, $d(E_0)$, and $\dfrac{d(E)}{1 - \mu\beta}$ becomes $\dfrac{d(E_0)}{1 - \mu\beta}$ which is $\dfrac{D_0}{1 - \mu\beta}$. This relationship is approximate because the voltage at the input without feed-back is free from distortion and with feed-back it is not and, hence, the assumption that the modulation is a function *only of the signal output* used in deriving eq 2 is not necessarily justified.

From the relationship $D = \frac{D_0}{1 - \mu\beta}$, it is to be concluded that modulation with feed-back will be reduced decibel for decibel as the effect of feed-back action causes an arbitrary db reduction in the gain of the amplifier; i. e., when the feed-back is negative. With positive feed-back the opposite is true, the modulation being increased by an amount corresponding to the increase in amplification.

If modulation in the β-circuit is a factor, it can be shown that usually in its effect on the output the modulation level at the output due to nonlinearity of the β-circuit is approximately $\frac{\mu\beta}{1 - \mu\beta}$ multiplied by the modulation generated in the β-circuit acting alone and without feed-back.

ADDITIONAL EFFECTS

Noise. A criterion of the worth of a reduction in noise is the reduction in signal-to-noise ratio at the output of an amplifier. Assuming that the amount of noise introduced is the same in 2 systems, for example, with and without feed-back, respectively, and that the signal outputs are the same, a comparison of the signal-to-noise ratios will be affected by the amplification between the place at which the noise enters and the output. Denoting this amplification by a and a_0, respectively, it can be shown that the relation between the 2 noise ratios is $\frac{a_0}{a}(1 - \mu\beta)$. This is called the *noise index.*

If noise is introduced in the power supply circuits of the last tube, $a_0/a = 1$ and the noise index is $(1 - \mu\beta)$. As a result of this relation less expensive power supply filters are possible in the last stage.

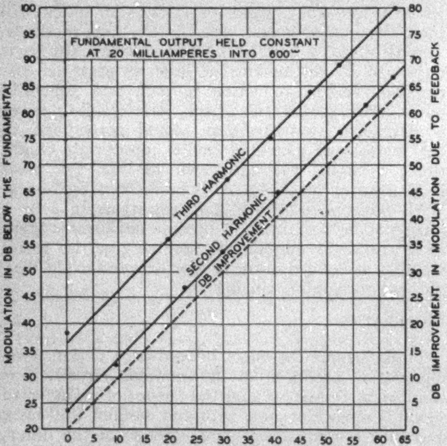


Fig. 8. Improvement of harmonics with feed-back

One example of another amplifier in which, with 60-db feed-back, harmonic currents in the output are only 1 thousandth and their energy 1 millionth of the values without feed-back

Phase Shift, Envelope Delay, Delay Distortion. In the expression $A_r = \left[\frac{\mu}{1 - \mu\beta}\right] \underline{|\theta}$, θ is the over-all phase shift with feed-back, and it can be shown that the *phase shift through the amplifier with feed-back may be made to approach the phase shift through the β-circuit plus 180 deg.* The effect of phase shift in the β-circuit is not reduced correspondingly. It will be recalled that in reducing the change in phase shift with frequency, envelope delay, which is the slope of the phase shift with respect to the angular velocity, $\omega = 2\pi f$, also is reduced. The *delay* distortion likewise is reduced because a measure of delay distortion at a particular frequency is the difference between the envelope delay at that frequency and the least envelope delay in the band.

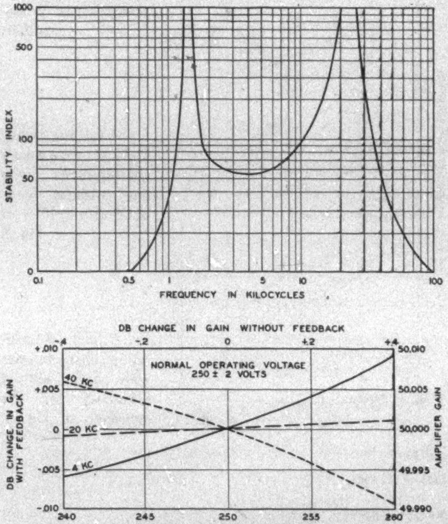


Fig. 9. Representative gain stability of a single amplifier as determined by measuring 69 feed-back amplifiers in tandem at Morristown, New Jersey

The upper figure shows the absolute value of the stability index. It can be seen that between 20 and 25 kc the improvement in stability is more than 1,000 to 1 yet the reduction in gain was less than 35 db

The lower figure shows change in gain of the feed-back amplifier with changes in the plate battery voltage and the corresponding changes in gain without feed-back. At some frequencies the change in gain is of the same sign as without feed-back and at others it is of opposite sign and it can be seen that near 23 kc the stability must be perfect

β-Circuit Equalization. Referring to eq 2, the output voltage E approaches $-e_0/\beta$ as $1 - \mu\beta = -\mu\beta$ and equals it in absolute value if $\cos\Phi = \frac{1}{2|\mu\beta|}$

where $\mu\beta = |\mu\beta| \underline{|\Phi}$. Under these circumstances increasing the loss in the β-circuit 1 db raises the gain of the amplifier 1 db, and *vice-versa*, thus giving any gain-frequency characteristic for which a like loss-frequency characteristic can be inserted in the β-circuit. This procedure has been termed β-circuit equalization. It possesses other advantages and properties which are beyond the scope of this paper.

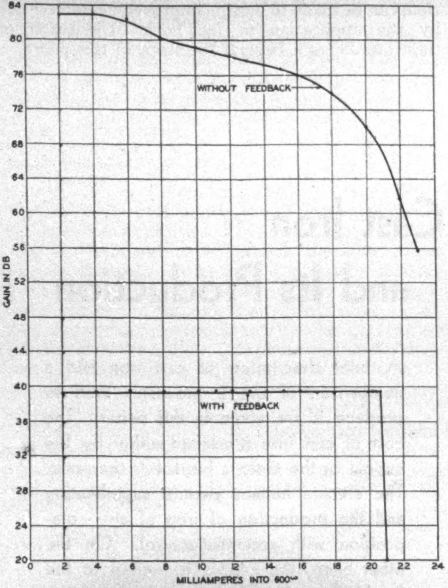


Fig. 10. Gain-load characteristic with and without feed-back for a low level amplifier designed to amplify frequencies from 3.5 to 50 kc

AVOID SINGING

Having considered the theory up to this point, experimental evidence was readily acquired to demonstrate that $\mu\beta$ might assume large values, 10 to 10,000, provided Φ was not at the same time zero. However, one noticeable feature about the field of $\mu\beta$ (Figs. 3 and 4) is that it implies that even though the phase shift is zero and the absolute value of $\mu\beta$ exceeds unity, self-oscillations or singing will not result. This may or may not be true. When first thinking about this matter it was suspected that owing to practical nonlinearity, singing would result whenever the gain around the closed loop equaled or exceeded the loss and simultaneously the phase shift was zero; i. e., $\mu\beta = |\mu\beta| + j\text{o} \geq 1$. Results of experiments, however, seemed to indicate something more was involved and these matters were described to H. Nyquist who developed a more general criterion for freedom from instability applicable to an amplifier having linear positive constants. (For a complete description of the criterion for stability and instability and exactly what is meant by enclosing the point (1, 0), reference should be made to Regeneration Theory, by H. Nyquist. *Bell System Technical Journal*, v. XI, July 1932, p. 126–47.)

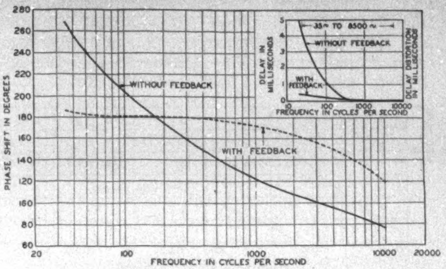


Fig. 11. Phase shift, delay, and delay distortion with and without feed-back for a single tube voice frequency amplifier

To use this criterion, plot $\mu\beta$ (the modulus and argument vary with frequency) and its complex conjugate in polar coördinates for all values of frequency from 0 to $+\infty$. If the resulting loop or loops do not enclose the point (1, 0) the system will be stable, otherwise not. The envelope of the transient response of a stable amplifier always dies away exponentially with time; that of an unstable amplifier in all physically realizable cases increases with time. Characteristics A and B in Fig. 5 are results of measurements on 2 different amplifiers; the amplifier having $\mu\beta$ characteristic denoted A was stable, the other unstable.

The number of stages of amplification that can be used in a single amplifier is not significant except in so far as it affects the question of avoiding singing. Amplifiers with considerable negative feed-back have been tested where the number of stages ranged from 1 to 5, inclusive. In every case the feed-back path was from the output of the last tube to the input of the first tube.

EXPERIMENTAL RESULTS

Figs. 6 and 7 show how the gain-frequency and modulation characteristics of the 3-stage impedance coupled amplifier of Fig. 2 are improved by negative feed-back. In Fig. 7 the improvement in harmonics is not equal exactly to the decibel reduction in gain. Fig. 8 shows measurements on a different amplifier in which harmonics are reduced as negative feed-back is increased, decibel for decibel over a 65-db range.

That the gain with frequency practically is independent of small variations in $|\mu|$ is shown by Fig. 9. This is a characteristic of the Morristown amplifier, described in the paper by Clark and Kendall referred to previously, which meets the severe requirements imposed upon a repeater amplifier

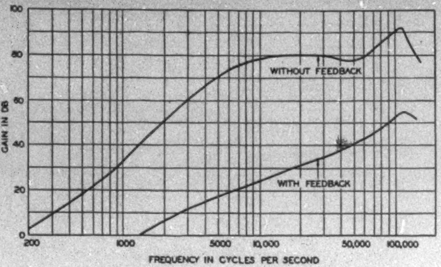


Fig. 12. Gain-frequency characteristic of an amplifier with an equalizer in the β-circuit

This was designed to have a gain frequency characteristic with feed-back of the same shape as the loss frequency characteristic of a nonloaded telephone cable

for use in cable carrier systems. Designed to amplify frequencies from 4 kc to 40 kc the maximum change in gain due to variations in plate voltage does not exceed $\frac{7}{10{,}000}$ db per volt and at 20 kc the change is only $\frac{1}{20{,}000}$ db per volt. This illustrates that for small changes in $|\mu|$, the ratio of the stability without feed-back to the stability with feed-back, called the *stability index*, approaches $\frac{|1-\mu\beta|^2}{1-|\mu\beta|\cos\Phi}$ and gain stability is improved at least as much as the gain is reduced and usually more, and is theoretically perfect if $\cos\Phi = \frac{1}{|\mu\beta|}$.

In Fig. 10 is indicated the effectiveness with which the gain of a feed-back amplifier can be made independent of variations in input amplitude practically up to the overload point of the amplifier. These measurements were made on a 3-stage amplifier designed to work from 3.3 kc to 50 kc.

As shown in Fig. 11, the negative feed-back may be used to improve phase shift and reduce delay and delay distortion. These measurements were made on an experimental 1-tube amplifier, 35–8,500 cycles, feeding back around the low side windings of the input and output transformers.

In Fig. 12 is given the gain-frequency characteristic of an amplifier with and without feed-back when in the β-circuit there is an equalizer designed to make the gain-frequency characteristic of the amplifier with feed-back of the same shape as the loss-frequency characteristic of a nonloaded telephone cable.

CONCLUSION

The feed-back amplifier dealt with in this paper was developed primarily with requirements in mind for a cable carrier telephone system, involving many amplifiers in tandem with many telephone channels passing through each amplifier. Most of the examples of feed-back amplifier performance naturally have been drawn from amplifiers designed for this field of operation. In this field, vacuum tube amplifiers normally possessing good characteristics with respect to stability and freedom from distortion are made to possess superlatively good characteristics by application of the feed-back principle.

However, certain types of amplifiers, in which economy has been secured by sacrificing performance characteristics, particularly as regards distortion, can be made to possess improved characteristics by the application of feed-back. Discussion of these amplifiers is beyond the scope of this paper.

Cast Iron and Its Production

A brief description of cast iron and a comparison of the 2 processes used to produce it are given in this paper. The cost of cast iron produced either by the cupola or the electric furnace is the same. The electric furnace permits superheating and the production of iron of any composition with accurate control. On the other hand, the cupola is limited to the production of high carbon iron. As a result of the success of electric melting, the field of application of cast iron has been greatly increased.

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THE late Dr. Moldenke was probably the first to advance the theory that the superheating of cast iron dissolves the carbon nucleuses that are the cause of coarse graphitization and nonuniformity. In recent years the electric furnace has made possible a thorough examination of this theory, and the results indicate not only that the theory is correct, but that it has enabled the regular production of a new and reliable quality of cast iron. The data in this paper have been accumulated in the last 2 years,

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Full text of a paper recommended for publication by the A.I.E.E. committee on electrochemistry and electrometallurgy, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 14, 1933; released for publication Dec. 7, 1933. *Not published in pamphlet form.*

during which time a cupola and an electric furnace have been operated in parallel and the results recorded.

THE CHARACTERISTICS OF CAST IRON

The following brief description of cast iron is included in order to provide a common basis upon which the comparison of cupola and electric furnace melting may be judged.

Cast iron in the molten state is a solution of carbon, silicon, and manganese in iron. The proportions of these elements, disregarding impurities, are within the limits noted below:

Carbon—1.7 to 3.6 per cent
Silicon—1.6 to 3.0 per cent
Manganese—0.50 to 1.0 per cent
Iron—remainder

Other elements, particularly phosphorus and sulphur, are present as impurities.

As the temperature is lowered, the alloy passes from the state of solution to an aggregate or mixture in the solid, becoming, if cooled with sufficient slowness down to and through the critical range, a complete aggregation as exhibited by the iron-carbon constitutional diagram. This phenomenon of change from a solution to an aggregate is the basis of the consideration of the electric furnace for the manufacture of cast iron.

As cast iron cools from the solidification temperature, there is a progressive rejection of carbon from solution or combination with the iron to the free form of graphite. This rejection ceases at the gamma-alpha transformation temperature. The amount of carbon in the combined form at this point varies with the composition, particularly silicon, and with the rate of cooling. For maximum machinability, it should be zero and for maximum strength it should be the eutectoid, that is, 0.65 to 0.85 per cent. Usually more carbon is left combined than is desired, particularly at the surface of the casting, and a subsequent heat treatment is applied to reduce it to the proper amount. The retention of the major portion of the carbon in the combined form must be avoided in the original cooling. Adjustment of composition to casting size is necessary since the rate of cooling is dependent upon the section cast. The limits of composition are as noted previously.

Certain alloying elements such as nickel, molybdenum, and chromium are often used singly or in combination in cast iron for their effect on graphitization and the shape of the resultant graphite flakes. Their use necessitates an adjustment of composition in the other elements. Nickel can be used to replace the silicon in part. Its value lies in the fact that it is a graphitizer for combined carbon in excess of the eutectoid. Molybdenum has the property of "balling up" the graphite flakes, thereby increasing the strength without adding materially to the hardness. Chromium is a drastic inhibitor to graphitization. In the great majority of cases, the use of alloying elements is an unnecessary expense, as the improvements desired can be obtained by adjustment of composition and by superheating, as will be described later.

In the process of cooling, cast iron becomes a

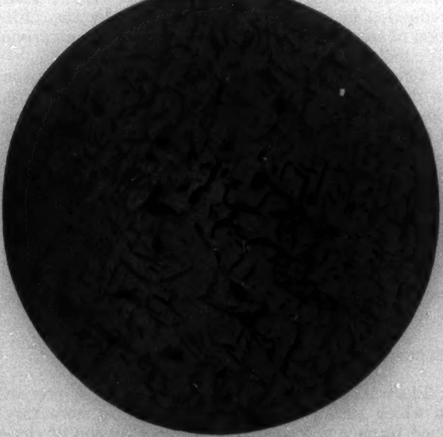

Fig. 1. Photomicrograph unetched of a specimen taken from the surface of a 2-in. wall section of cupola cast iron

Total carbon—3.16 per cent; silicon—2.13 per cent; manganese—0.62 per cent. Tensile strength—28,000 lb per square inch. Magnified slightly over 100 diameters

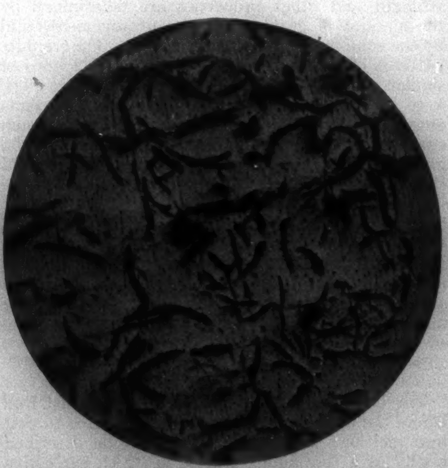

Fig. 2. Photomicrograph unetched of a specimen taken from the center of the same casting as in Fig. 1

Tensile strength—23,000 lb per square inch. Magnified slightly over 100 diameters

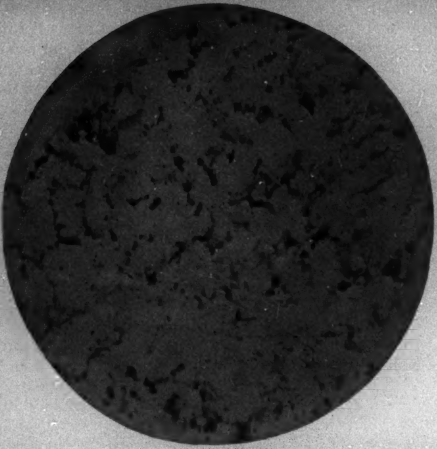

Fig. 3. Photomicrograph unetched of a specimen taken from the surface of a 2-in. wall section of cast iron which has been superheated in the electric furnace

Total carbon—3.24 per cent; silicon—2.22 per cent; manganese—0.60 per cent. Tensile strength—36,000 lb per square inch. Magnified slightly over 100 diameters

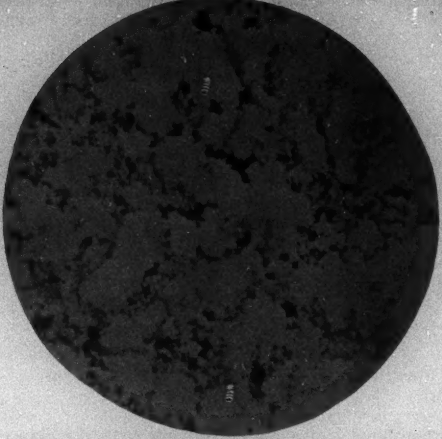

Fig. 4. Photomicrograph unetched of a specimen taken from the center of the same casting as in Fig. 3

Tensile strength—34,000 lb per square inch. Magnified slightly over 100 diameters

nonductile aggregate, consisting of a ferritic to pearlitic matrix whose continuity is interrupted by the presence of graphite flakes. Obviously, the strength and other properties are determined by the amount of graphite, by its arrangement, and by the combined carbon in the matrix. The graphite patterns of skin and center specimens of 2 irons of similar composition and section are shown in Figs. 1 to 4. The superheated iron, having the same amount of graphite as the cupola iron, is much stronger by reason of the better arrangement of its graphite. The uniformity across the section should be noted. All other factors being constant, the strength of iron varies inversely with the amount of graphite present. In Fig. 5 is shown the unetched microstructure of a low-carbon superheated iron, which has the advantage of good arrangement and low graphite content. Cast iron of maximum strength must have a eutectoid matrix and the minimum of graphite which is finely dispersed.

CUPOLA MELTING

The cupola was the principal source of cast iron before the application of the electric furnace to cast iron melting. Cupola operation can be described briefly as a continuous process in which successive charges are melted in the presence of carbon by combustion of the carbon. The maximum temperature obtainable is approximately 1,500 deg C. The capacity varies directly with the hearth area. A 60-in. cupola can produce 20,000 lb of iron per hour. The average charge consists of 50 per cent pig iron and 50 per cent selected iron and steel scrap. The components of this charge must be sized to obtain even melting conditions. They must be of known composition, since control of composition of the product substantially ends with the selection of the charge. A change from one grade of iron to another is gradual, since the charges tend to become mixed while descending to the melting zone. While some reduction in carbon may be obtained by the addition of steel to the charge, the lower limit for carbon in cupola iron is practically 3.0 per cent.

The solution of the last traces of carbon in iron is difficult, requiring both time and temperature. Solution may be accomplished in 10 to 15 min at 1,650 deg C. A longer time is necessary at a lower temperature. As a result of the low temperature available and the intimate contact with the coke, cupola iron comes from the spout bearing undissolved carbon in suspension. The suspended particles, after solidification of the iron, act as nucleuses for the crystallization of precipitating graphite resulting in a coarse structure, particularly in the center of a casting where the rate of cooling is slow (see Figs. 1 and 2).

ELECTRIC FURNACE MELTING

Electric furnace melting is a batch melting process in which the cold charge is placed in a refractory lined furnace and melted by the conversion of electrical energy to heat. Two types of electric furnaces are in general use for making cast iron: the indirect-arc single-phase and the direct-arc 3-phase types. In the former, the arc is maintained between like electrodes above the charge. In the latter, the arc is maintained between the electrodes and the charge.

Cast iron of any composition from 1.7 to 3.6 per cent carbon can be produced readily and accurately, since the electric furnace simply melts what is in it. The composition of the bath can be altered as and when desired. A charge of unknown composition can be melted and held until the analysis is completed and adjustments made. The charge for melting can be of low-cost materials such as borings, turnings, punchings, and any other scrap that may be available.

A heat of cast iron in an electric furnace, when just melted, has the same characteristics as cupola iron of a like analysis. It has undissolved carbon in suspension which acts as nucleuses for coarse graphitization. If the bath is heated to approximately 1,650 deg C and held for 10 min, the suspended carbon is dissolved. This heating to obtain complete solution is known as superheating. Cast iron when so treated has no nucleuses to attract precipitating graphite. It is, therefore, fine grained and uniform throughout, as shown in Figs. 3 and 4.

COMPARATIVE COSTS

The cost data shown in Table I are based upon the operation of a 3-ton 3-phase direct-arc electric furnace delivering 5 tons of metal every 3 hr. The energy, delivered to the transformer at 10,300 volts and 40 cycles, is transformed to 150 volts for melting and 100 volts for refining. The current maintained in the furnace is 6,000 amp. Charging, at the present, is done by hand. This operation takes approximately 30 min. The time consumed in melting and refining averages 2 hr. Tapping and conditioning the furnace accounts for the remaining 30 min. The cupola data were obtained from the operation of a 60-in. cupola using a 32-in. bed charge of coke and a 1 to 9 ratio of coke to metal in the charge. The blast pressure was 15 lb per square inch delivered through 8 tuyères. This cupola melted approximately 20,000 lb of metal per hour.

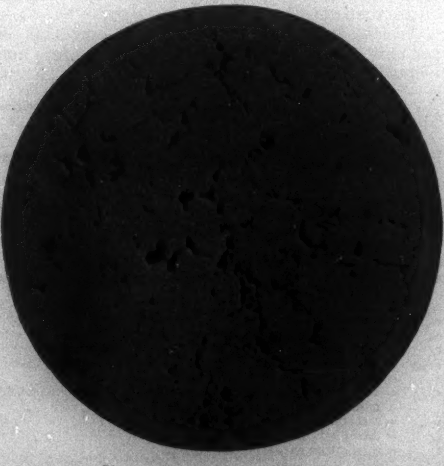

Fig. 5. Photomicrograph unetched of a specimen taken from the center of a 2-in. section of low-carbon cast iron

Total carbon—2.18 per cent; silicon—2.20 per cent; manganese—1.00 per cent. Tensile strength—62,000 lb per square inch. Magnified slightly over 100 diameters

Table I—Comparative Costs of Operation

	Cost per Net Ton	
	Electric Furnace	Cupola
Energy, 600 kwhr at 1¢ per kwhr	$ 6.00	
Labor	1.35	$ 1.20
Fuel, coke at $10 per ton		1.64
Maintenance, including refractories	1.10	0.70
Electrodes, 8 lb per ton at 10¢ per lb	0.80	
Conversion cost	$ 9.25	$ 3.54
Material for melting	7.28	12.89
Total	$16.53	$16.43

The conversion cost of the electric furnace, in this case, is higher than the conversion cost of the cupola by approximately the item for electrical energy. The lower cost of the material for melting very nearly brings the totals to the same figure. While the data contained herein are true for one locality only, they are believed to be representative of what can be expected in the ordinary manufacturing plant producing a wide variety of scrap which can be used to advantage in electric melting.

SUMMARY

The information given in this paper may be summarized as follows:

1. Cast iron of any carbon content throughout the range from 1.7 to 3.6 per cent can be produced readily and accurately in the electric furnace. The cupola is limited to the production of irons with carbon in excess of 3.0 per cent.

2. Cast iron produced in the cupola is coarse grained and nonuniform, because it is impossible to dissolve the suspension of carbon present in the molten metal. Superheating in the electric furnace dissolves this suspension and permits the production of a fine grained uniform material.

3. The cupola is an economical unit for the production of large quantities of cast iron of the type that can be made in the cupola.

4. The control of the electric furnace is positive, and uniformity of results can be guaranteed. The control of composition of the product in the cupola ends substantially with the selection of the charge for melting.

5. There is no great disparity in cost between melting in the electric furnace and in the cupola. The higher conversion cost of the one is substantially balanced by the higher melting material cost of the other.

6. On account of the success with electric melting, cast iron specifications are being revised with a view to making cast iron really an engineering material of definite properties. This means that the day's output of the ordinary foundry is to be of a wide range of compositions with close control that is not characteristic of cupola operation. The cupola can be depended upon for the production of large quantities of a high carbon material with little flexibility within a heat. Electric melting is very flexible. The character of a bath or any part of it can be altered readily to meet the needs of a varied production.

Equivalent Reactance of Synchronous Machines

Steady state characteristics of synchronous machines of normal design are affected appreciably by changes in magnetic saturation. In this paper the effect of saturation is included in the derivation of the equations for determining steady state performance. It is shown that a saturated machine under steady state conditions, and for small changes from the original operating point, can be replaced for purposes of calculation by an unsaturated machine.

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IT HAS BEEN recognized for sometime that consideration of the effect of saturation in synchronous machines is necessary to determine accurately the steady state stability characteristics of a system, and that the methods of analysis that neglect saturation lead to pessimistic results.[1,2,3,4] It is the purpose of this paper to present a method of analysis by which saturation effects may be taken into account in determining the steady state performance of a machine or system and to suggest equations for the equivalent reactances of synchronous machines in order that a rational comparison of their characteristics may be made.

Methods of analysis of system and machine steady state stability performance presented in previous papers[5,6,7,8] depend upon the linear relations existing between the currents and voltages. Saturation of the machines introduces nonlinearity. However, under steady state conditions an equivalent linear reactance may be used to represent the reactance of the machine at the particular operating condition for small changes of the initial quantities. This equivalent reactance is dependent not only upon the particular load, voltage, and power factor at which the machine is operating, but also upon the connected system. After the equivalent reactance is determined, calculations to determine the machine and system performance can be carried out in the usual manner. The following analysis shows the variation of this equivalent reactance with change in the characteristics of the system and the load on the machine. Finally, approximate formulas are developed so that a comparison of the equivalent reactances of machines can be made from the design data.

The concept of equivalent reactance is not new, as various empirical and graphical methods of adjusting the synchronous reactances of synchronous machines have been proposed. Miss Edith Clarke, in a discussion[2] in 1926, presented an empirical formula, suggested by C. A. Nickle, for the equivalent reactance of synchronous machines to be used in making stability calculations. This empirical formula is almost equivalent to the expression derived in the following analysis for the case of cylindrical-rotor or salient-pole machines when operating as synchronous condensers, but is inapplicable to the case of synchronous motors or generators operating at normal power factors. Dahl[3] and Dwight[4] also have presented methods based on charts and semiempirical methods for correcting for generator saturation. Since these empirical or semiempirical methods neglect important factors, it was thought desirable to have a more rational method available by which the equivalent reactance for a given load condition may be determined from the design data of the machine under consideration and which shows directly the factors which determine its value.

MATHEMATICAL ANALYSIS

In the following analysis the cylindrical-rotor and salient-pole synchronous machines are considered separately, the cylindrical-rotor case first because of its comparative simplicity.

Nomenclature. All quantities are expressed in per unit on the machine normal kilovoltampere and voltage base.

$\frac{a}{b} = \frac{e_l}{k}\frac{\partial k}{\partial e_l} =$ ratio of intercept cut by tangent to load saturation curve. (Fig. 2.)
$\frac{a_1}{b_1} = \frac{e_l}{k_1}\frac{\partial k_1}{\partial e_l} =$ ratio of intercept cut by tangent to stator saturation curve
$\frac{a_2}{b_2} = \frac{e_{ld}}{k_2}\frac{\partial k_2}{\partial e_{ld}} =$ ratio of intercept cut by tangent to rotor load saturation curve
e_s = system voltage
$e_{(l_q)}$ = voltage corresponding to equivalent field mmf
e_l = voltage corresponding to the air gap flux (behind leakage reactance)
e_{ld} = direct axis component of e_l
e_{lq} = quadrature axis component of e_l
e_t = terminal voltage of machine
e_d = voltage corresponding to direct axis field mmf
$e_{d(eq)}$ = voltage corresponding to equivalent direct axis field mmf
e_q = voltage corresponding to quadrature axis field mmf
$e_{q(eq)}$ = voltage corresponding to equivalent quadrature axis field mmf
i = armature current
i_d = direct axis armature current
i_q = quadrature axis armature current
$k = 1 + \frac{\text{iron mmf}}{\text{air gap mmf}}$
$k_1 = 1 + \frac{\text{iron mmf in the stator}}{\text{air gap mmf}}$
$k_2 = 1 + \frac{\text{iron mmf in the rotor}}{\text{air gap mmf}}$
r_a = machine armature resistance

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[1] For references see end of paper.

r_e = external resistance
x_e = external reactance
x_{eq} = equivalent reactance
x_l = leakage reactance
x_d = direct axis synchronous reactance
$x_{d(eq)}$ = equivalent direct axis synchronous reactance
x_q = quadrature axis synchronous reactance
$x_{q(eq)}$ = equivalent quadrature axis synchronous reactance
β = angle between e_d and e_l
θ = power factor angle of machine (angle between e_t and i).
ϕ = angle between e_l and i
δ = angle between e_d and e_e
δ_{eq} = angle between e_{eq} and e_e

Cylindrical-Rotor Synchronous Machine. The following assumptions are made for the case of the cylindrical-rotor synchronous machine.

1. The quadrature axis magnetic reluctance is equal to the direct axis reluctance, $x_d = x_q$. (For all symbols see foregoing nomenclature.)

2. The armature reaction mmf is proportional to a reactive voltage drop equal to $(x_d - x_l)i$.

3. The field current is maintained constant for the small changes being considered.

4. The vector difference of the armature reaction mmf and the mmf due to the field current is an mmf which is proportional to k times the voltage behind the leakage reactance drop. Where

$$k = 1 + \frac{\text{iron mmf}}{\text{air gap mmf}}$$

5. The iron mmf in the machine is a function only of the total air gap flux and the field current.

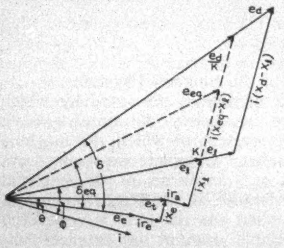


Fig. 1. Steady state vector diagram of a cylindrical-rotor synchronous generator with saturation

On the basis of these assumptions the vector diagram of Fig. 1 can be drawn. From the vector diagram the following equation can be written for the field excitation,

$$e_d = \sqrt{(ke_l)^2 + i^2(x_d - x_l)^2 + 2ke_li(x_d - x_l)\sin\phi} \qquad (1)$$

e_l, i, ϕ are variables and k is a function of the total air gap flux, e_l, and the field excitation, e_d. However, since only steady state conditions with constant field current are considered in this analysis, k is a function of only one variable, the total air gap flux e_l.

Therefore, for small changes eq 1 yields

$$2e_dde_d = [ke_l + i(x_d - x_l)\sin\phi]\left[k + e_l\frac{\partial k}{\partial e_l}\right]de_l + [i(x_d - x_l)^2 + ke_l(x_d - x_l)\sin\phi]\,di + [ke_li(x_d - x_l)\cos\phi]\,d\phi \qquad (2)$$

Letting $de_d = 0$ in accordance with assumption 3 and substituting eq A-6 from Appendix A in eq 2 for $\frac{\partial k}{\partial e_l}$.

$$0 = [ke_l + i(x_d - x_l)\sin\phi]\left[1 + \frac{a}{b}\right]kde_l + [i(x_d - x_l)^2 + ke_l(x_d - x_l)\sin\phi]\,di + [ke_li(x_d - x_l)\cos\phi]\,d\phi \qquad (3)$$

Where $\frac{a}{b}$ is a ratio obtained by drawing a tangent to the constant field current saturation curve at e_l. (See Fig. 2.)

Equation 3 is the differential equation governing the operating characteristics of a saturated cylindrical-rotor machine for small and gradual changes in the load conditions, with constant field excitation e_d.

If in eq. 3, $k = 1$, $\frac{a}{b} = 0$, the conditions for no saturation, and $x_d = x_{eq}$, eq 4 is obtained for an equivalent unsaturated machine.

$$0 = [e_l + i(x_{eq} - x_l)\sin\phi]\,de_l + [i(x_{eq} - x_l)^2 + e_l(x_{eq} - x_l)\sin\phi]\,di + [e_li(x_{eq} - x_l)\cos\phi]\,d\phi \qquad (4)$$

Equation 4 is the differential equation governing the operating characteristics of an equivalent unsaturated machine for small and gradual changes away from the operating point, holding a constant value of field excitation, e_{eq}.

This equivalent unsaturated machine is one which has no saturation, but has the same operating characteristics as the actual saturated machine at the operating point under consideration. Such a machine responds to small changes in the load conditions just as the saturated one does: thus it can be used to replace the actual saturated machine at the particular operating conditions. The values of e_l, i, and θ are identical for both machines, but the values of reactance x_{eq} and excitation e_{eq} for the equivalent unsaturated machine generally are less than the corresponding values x_d and e_d for the actual saturated machine. (See Fig. 1.) The equivalent reactance x_{eq} is the synchronous reactance of the equivalent unsaturated machine and can be used in the usual linear equations for determining the characteristics of the saturated machine. The equivalent reactance obviously is different for each operating point of the actual or saturated machine.

The equivalent reactance x_{eq} must, therefore, be such as to satisfy the simultaneous differential eqs 3 and 4. However, eqs 3 and 4 alone cannot be solved simultaneously to obtain x_{eq} but another independent relation between de_l, di, and $d\phi$ must be obtained. For example, if the system to which the machine under consideration is connected is such that $\phi = 90°$ and $d\phi = 0$, or $\phi = 0$ and $di = 0$,

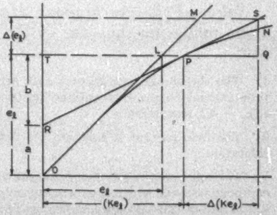


Fig. 2. Method of obtaining a/b. Load saturation curve for a cylindrical - rotor synchronous generator at constant field excitation E_d

$$x_{eq} = x_l + \frac{x_d - x_l}{k\left[1 + \frac{a}{b}\right]} \qquad (5)$$

or when $\phi = 0$ and $d\phi = 0$

$$x_{eq} = x_l + \frac{x_d - x_l}{k\sqrt{1 + \frac{a}{b}}} \tag{6}$$

or if $de_l = 0$

$$x_{eq} = x_l + \frac{x_d - x_l}{k} \tag{7}$$

The condition that $\phi = 90°$ and $d\phi = 0$ is realized by a synchronous condenser. Therefore, the equivalent reactance of a cylindrical-rotor synchronous condenser is given by eq 5 and is independent of the connected system. The condition that $de_l = 0$, eq 7, is most closely realized by a machine having a small value of x_l and connected directly to an infinite bus. Equation 6 is an intermediate or average value for x_{eq}, and may be used for the approximate determination of x_{eq} for cylindrical-rotor machines, with the exception of condensers, operating over a normal power factor range and connected to a system.

If a more accurate determination of x_{eq} is required than can be obtained by the approximate formulas, eqs 3 and 4 may be solved simultaneously with another relation depending upon the connected system similar to eq B-4 presented in Appendix B. It is suggested that eq 6 be used for the determination of x_{eq} when comparing the ability of cylindrical-rotor generators or motors to remain in static equilibrium for systems whose characteristics are not definitely known.

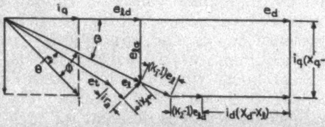


Fig. 3. Steady state vector diagram of a salient-pole synchronous generator with saturation. Zero quadrature axis field excitation

Salient-Pole Synchronous Machine. The assumptions made for the case of the salient-pole machine are:

1. The direct and quadrature axis armature reaction mmf's are proportional to reactive voltage drops equal to $i_d(x_d - x_l)$ and $i_q(x_q - x_l)$, respectively.
2. The field current is constant for the small changes under consideration.
3. The mmf required to overcome saturation can be divided into 2 components: one which is dependent only on the total flux, the other a function of the field mmf as well as the direct axis flux. The first is represented by the stator core and teeth, the second by the rotor pole piece. This assumption is made possible by the fact that there is very little saturation in the quadrature axis magnetic path in the rotor, i. e., in the pole tips. Most of the saturation in the rotor exists in the body of the pole, at and near the base, which is in the path of the direct axis flux. Under steady state conditions the second component of mmf may be considered as a function of the direct axis flux alone, with the total field mmf as a fixed parameter for a given load condition.

On the basis of these assumptions the vector diagram of Fig. 3 can be drawn. From the vector diagram the following relation can be written for the direct axis.

$$e_d = (k_1 + k_2 - 1)\, e_{ld} + (x_d - x_l)\, i_d \tag{8}$$

In a manner similar to that for the cylindrical-rotor case, eq 8 can be used to determine the equivalent direct axis reactance for a salient-pole synchronous condenser and an approximate expression obtained for the case of a generator or motor operating over the normal power factor range when connected to a system. These 2 expressions are derived in Appendix C and are as follows; for the salient-pole synchronous condenser,

$$x_{d(eq)} = x_l + \frac{x_d - x_l}{\left[k_1\left(1 + \frac{a_1}{b_1}\right) + k_2\left(1 + \frac{a_2}{b_2}\right) - 1\right]} \tag{9}$$

Equation 9 can be reduced to an expression identical to eq 5 for the cylindrical-rotor synchronous condenser as $k = k_1 + k_2 - 1$ and $k\frac{a}{b} = k_1\frac{a_1}{b_1} + k_2\frac{a_2}{b_2}$ since in this case $e_l = e_{ld}$. For the salient-pole motor or generator,

$$x_{d(eq)} \cong x_l + \frac{x_d - x_l}{\left[k_1\left(1 + \frac{a_1}{2b_1}\right) + k_2\left(1 + \frac{a_2}{b_2}\right) - 1\right]} \tag{10}$$

If there is no saturation in the stator teeth or core, all of the saturation being in the rotor pole piece in the path of the direct axis flux, eq 10 reduces to

$$x_{eq} = x_l + \frac{x_d - x_l}{k_2\left(1 + \frac{a_2}{b_2}\right)} \tag{11}$$

and is independent of the connected system.

In Appendix D a method is presented by which $x_{d(eq)}$ may be more accurately determined when the constants of the system to which the machine is connected are known. Complete expressions are given for $x_{d(eq)}$ and $x_{q(eq)}$ in terms of the external reactance and resistance x_e and r_e. For most practical purposes when the machine is connected through an appreciable amount of external impedance, $x_{q(eq)}$ may be considered equal to the unsaturated value x_q, as the synchronizing power coefficient $dP/d\delta$ is practically the same whether $x_{q(eq)}$ or x_q is used in its determination. It is suggested, however, as in the cylindrical rotor case, that when the characteristics of the system are not known eq 10 be used to obtain an approximate value of $x_{d(eq)}$ for salient-pole generators and motors.

Fig. 4. Vector diagram for an equivalent salient-pole synchronous machine

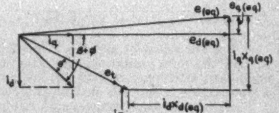


Fig. 4 shows a vector diagram of the equivalent unsaturated salient-pole machine. This machine has values of $x_{d(eq)}$ and $x_{q(eq)}$ such as to give the same response to changes at its terminals as the actual or saturated machine. Since $x_{d(eq)}$ and $x_{q(eq)}$ are

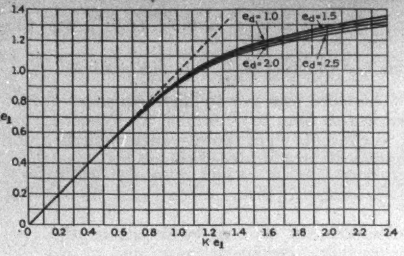


Fig. 5. With constant field excitation e_d

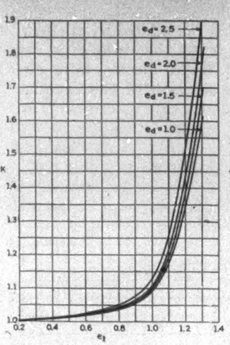


Fig. 6. Saturation factor K

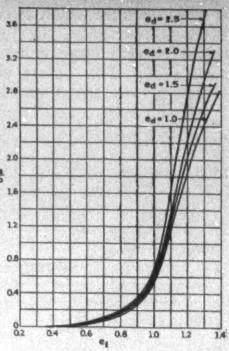


Fig. 7. Saturation factor a/b

Figs. 5, 6, and 7. Load saturation curves for cylindrical-rotor synchronous generator

different from x_d and x_q, respectively, while i, i_d, i_q, e_t, and θ are the same, $e_{d(eq)}$ and $e_{q(eq)}$ will be different from the e_d and e_q of the actual machine. In practically all commercial machines $e_q = 0$. Therefore, since $x_{q(eq)}$ is different from x_q, and i_q is the same for both the actual and equivalent machine, the equivalent machine may have excitation $e_{q(eq)}$ in the quadrature axis.

APPLICATION OF MATHEMATICAL ANALYSIS

In order to demonstrate the use of the formulas presented in the first part of this paper a numerical example will be worked out in detail for the cylindrical-rotor case.

A cylindrical-rotor synchronous generator is delivering rated kilovoltamperes at normal terminal voltage and 0.80 power factor to a system which may be represented, as far as effects at the generator terminals are concerned, by an equivalent external impedance of $0.10 + j\,0.50$ and constant voltage e_e. It is desired to determine the synchronizing power coefficient of the machine. The saturation curves for the generator for various values of e_t and e_d are shown in Fig. 5. From these curves, values of k are obtained directly as the ratio of ke_t to e_t and plotted against e_t for various values of e_d as shown in Fig. 6. From the curves in Fig. 5 tangents can be drawn, as described in Appendix A, whose intercepts on the e_t axis give the values of (a) and (b). The ratios $\frac{a}{b}$ then are plotted against e_t for various values of e_d as shown in Fig. 7. For the machine being considered, $x_d = 1.11$, $x_l = 0.11$, $r_a = 0$. From the vector diagram, Fig. 1.

$$e_l = \sqrt{(e_t \cos\theta + ir_a)^2 + (e_t \sin\theta + ix_l)^2}$$

$$= 1.07$$

$$\phi = \sin^{-1}\frac{e_t \sin\theta + ix_l}{e_l}$$

$$= 41.5°$$

From the curves of Fig. 5, for $e_t = 1.07$ and $e_d = 2.05$ (assumed)

$$ke_l = 1.26$$

Therefore

$$k = \frac{1.26}{1.07} = 1.18$$

Also

$$e_d = \sqrt{(ke_l)^2 + i^2(x_d - x_l)^2 + 2\,ke_l i\,(x_d - x_l)\sin\phi}$$

$$= 2.07 \text{ (checking the assumed value of 2.05)}$$

From Fig. 7, for $e_l = 1.07$ and $e_d = 2.07$, $\frac{a}{b} = 1.13$.

The quantities to be substituted in eqs 3, 4, and B-4 now are all determined and are

$x_d = 1.11$ $x_e = 0.50$ $e_l = 1.07$

$x_l = 0.11$ $k = 1.18$ $i = 1.0$

$r_e = 0.10$ $1 + \frac{a}{b} = 2.13$ $\phi = 41.5°$

Substituting these quantities in eqs 3 and B-4 there results

$$-1.839 = 4.85\frac{de_l}{di} + 0.948\frac{d\phi}{di}$$

$$0.130 = 0.591\frac{de_l}{di} - 0.418\frac{d\phi}{di}$$

Solving the above 2 equations simultaneously

$$\frac{de_l}{di} = -0.25, \frac{d\phi}{di} = -0.66$$

Substituting these values in eq 4

$$(x_{eq} - 0.11)^2 + 0.0152\,(x_{eq} - 0.11) - 0.268 = 0$$

or

$$x_{eq} = 0.11 + 0.52 = 0.62$$

While eq 6 yields as an approximation

$$x_{eq} = 0.11 + \frac{1.11 - 0.11}{1.18\sqrt{2.13}} = 0.69$$

Figure 8 shows the variation in x_{eq} for this same turbine-generator when connected to a system through various values of external impedance $r_e + j\,x_e$. It will be noted that the system has a considerable influence on the equivalent reactance of the machine which is connected to it. For zero external reactance, the ratio of x_{eq} to x_d is 0.75, while for very large values of x_e, the ratio of x_{eq} to x_d is 0.39. The points on these curves were obtained by the simultaneous solution of the 3 equations presented in Appendix B in a manner similar to that for the foregoing case.

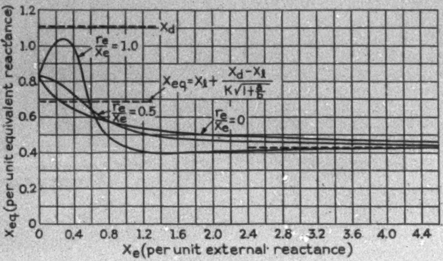


Fig. 8 (above). Equivalent reactance

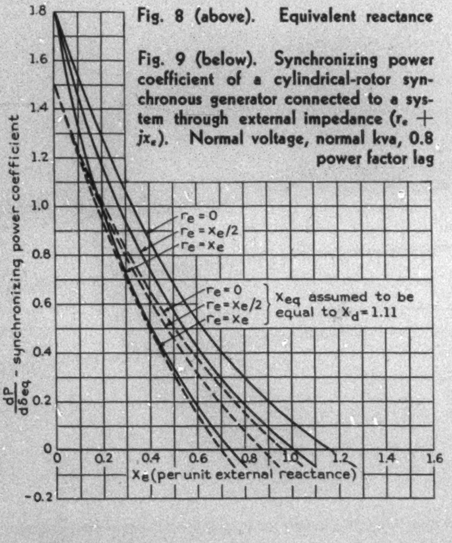


Fig. 9 (below). Synchronizing power coefficient of a cylindrical-rotor synchronous generator connected to a system through external impedance ($r_e + jx_e$). Normal voltage, normal kva, 0.8 power factor lag

The values of x_{eq} from Fig. 8 were used to calculate the values of synchronizing power coefficient,[5] $dP/d\delta_{eq}$, shown by the full lines in Fig. 9. The dotted lines show the pessimistic values of synchronizing power coefficient for the same typical large turbine generator, obtained by neglecting saturation, that is, by assuming $x_{eq} = x_d$.

In determining the synchronizing power coefficient the value of using the equivalent reactance is seen clearly. For example, the power angle equation for a saturated machine neglecting line and armature resistance is (see Fig. 1),

$$P = \frac{e_d e_e}{x_d - x_l + k\,(x_e + x_l)} \sin \delta \qquad (12)$$

In this equation k is a variable and $\frac{dP}{d\delta}$ for this machine is a function of $\frac{dk}{d\delta}$, an undetermined quantity. Therefore, the power angle equation cannot be used in this form to determine the synchronizing power coefficient. The power angle equation for the equivalent unsaturated machine is

$$P = \frac{e_{eq} e_e}{x_{eq} + x_e} \sin \delta_{eq} \qquad (13)$$

This equation can be used to determine the synchronizing power coefficient, as e_{eq} and x_{eq} are constants for small gradual changes from the particular load point being studied. That is,

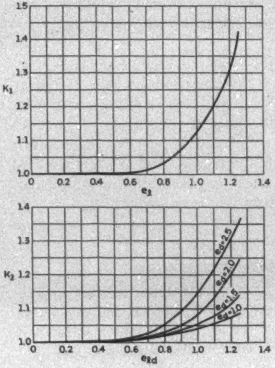
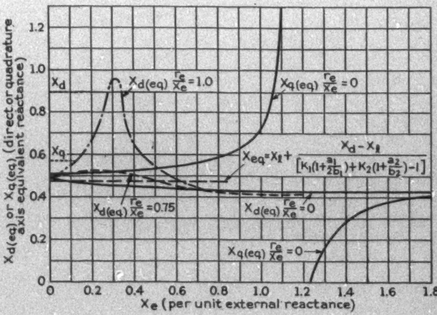


Fig. 10 (left). Saturation factors, k_1 and k_2, for large slow speed waterwheel - driven generator

Fig. 11 (below). Equivalent reactances of this machine connected to a system through external impedance ($r_e + jx_e$). Normal voltage, normal kva, and 0.8 power factor lag



$$\frac{dP}{d\delta} = \frac{e_{eq} e_e}{x_{eq} + x_e} \cos \delta_{eq} \qquad (14)$$

Therefore, the synchronizing power coefficient of a saturated machine can easily be written in terms of its equivalent reactance, excitation, and angle.

Fig. 10 shows the variation in k_1 and k_2 with change in e_1 and e_{1d}, respectively, for a large slow speed waterwheel generator. Fig. 11 shows the variation of the direct axis equivalent reactance of this machine when connected to a system through different amounts of external impedance when the machine is operating at rated output and field excitation. As in the cylindrical-rotor machine case the variation of $x_{d(eq)}$ is very large when the ratio of the external resistance to reactance approaches a value as high as unity. However, this ratio usually is considerably less than unity and the approximate equation for $x_{d(eq)}$ may be used with fair accuracy in most cases.

Although $x_{q(eq)}$ varies greatly it has very little effect on the synchronizing power coefficient of the machine when it is connected through a large external impedance, as is shown in Fig. 12, where the results of calculations using both $x_{d(eq)}$ and $x_{q(eq)}$ are compared with the results when $x_{d(eq)}$ and x_q(unsaturated) are used. Fig. 12 also shows the error involved if the effect of saturation is neglected altogether when calculating the synchronizing power coefficient, $\frac{dP}{d\delta}$.

The value of the equivalent reactance cannot easily be determined by test when a machine is operated under load connected to an external system. However, a test can be made at constant power factor and field current and a check made of the value of the equivalent reactance under these conditions. For a cylindrical-rotor machine at any constant power factor angle θ (see Appendix E)

$$x_{eq} = -\left(\frac{de_t}{di} + \frac{e_t}{i}\right)\frac{\sin\theta}{2} + \sqrt{\left(\frac{de_t}{di} + \frac{e_t}{i}\right)^2\left(\frac{\sin\theta}{2}\right)^2 - \frac{de_t}{di}\cdot\frac{e_t}{i}} \quad (15)$$

where $\frac{de_t}{di}$ is the rate of change of terminal voltage with armature current at constant power factor, cos θ, and constant field current, e_d. Therefore, from the coördinates and slope of the voltampere characteristic, the equivalent reactance for a cylindrical-rotor machine can be determined according to the above formula for the case of constant power factor.

For unity power factor eq 15 reduces to

$$x_{eq} = \sqrt{-\frac{de_t}{di}\cdot\frac{e_t}{i}} \quad (16)$$

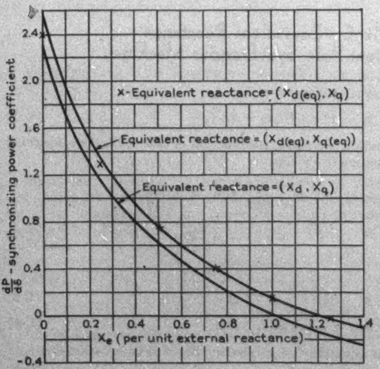


Fig. 12 (left). Synchronizing power coefficient of large slow speed water-wheel-driven generator connected to a system through external reactance. Normal voltage, normal kva, and 0.8 power factor lag

while for zero power factor

$$x_{eq} = -\frac{de_t}{di} \quad (17)$$

The above test values of equivalent reactance for the cylindrical-rotor machine may be predetermined by calculation by means of the equations given in Appendix E.

For salient-pole machines, the zero power factor test is the only test that can be made simply to determine x_{eq}. At zero power factor

$$x_{d(eq)} = -\frac{de_t}{di} \quad (18)$$

This value of equivalent reactance may be calculated by means of eq 9.

Equations 17 and 18 are identical with eq D-3 given in reference 5 for the equivalent reactance of a synchronous condenser.

Table I

Type of Machine	Voltage	Current	P.F.	x_d	Calculated Value of x_{eq}	Test Value of x_{eq}	$\frac{x_{eq}\text{ test)}}{x_d}$
Salient-Pole Water-Generator	1.0	1.0		0	0.90	0.36	0.37	0.41
Salient-Pole Condenser	1.0	1.0		0	1.92	0.71	0.70	0.36
Cylindrical-Rotor Generator	1.0	1.0	1.0	1.19	0.89	1.04	0.87
Cylindrical-Rotor Generator	1.0	1.0	1.0	0.74	0.57	0.63	0.85
Cylindrical-Rotor Generator	1.0	0.87	0	1.20	0.54	0.55	0.46
Cylindrical-Rotor Generator	1.0	0.66	0	1.22	0.79	0.77	0.63
Cylindrical-Rotor Generator	1.0	0.98	0	1.11	0.63	0.58	0.52
Cylindrical-Rotor Generator	1.0	1.0	0	0.77	0.45	0.40	0.52

Table I gives a comparison between the test and calculated values of the equivalent reactances for cylindrical-rotor and salient-pole machines operating at zero power factor overexcited, and at unity power factor.

CONCLUSIONS

1. Saturation of the magnetic circuit materially increases the steady state stability limits of synchronous machines. For example, for a typical relation of transmission line terminal reactances, the distance to which a given amount of power can be transmitted before the steady state stability limit is reached is about 25 per cent greater when saturation properly is allowed for, than if it is not taken into account.

2. As shown in the paper, the effects of saturation can accurately be taken into account by substituting a calculated equivalent value of reactance for the synchronous reactance. The ratio of this equivalent reactance to the synchronous reactance varies from about 0.4 for a synchronous condenser at full load and 0.6 for a generator at

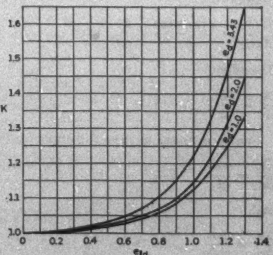


Fig. 13 (right). Saturation factor k for high speed salient-pole synchronous capacitor

full load to 0.8 or 1.0 for lightly loaded machines. A ratio of 0.8 generally has been used for motors and generators up to this time, but in the future it is planned to use the accurate values given by this theory for each particular case. For the typical relation of transmission line and terminal reactances, it is expected that this may give steady state power limits of the order of 10 per cent higher than if a factor of 0.8 had been used. Figs. 9 and 12 show the error introduced in determining the synchronizing power coefficient $\frac{dP}{d\delta}$ by neglecting saturation entirely. These machines both had a ratio of equivalent reactance to synchronous reactance of about 0.6. If a ratio of 0.8 had been used the error approximately would have been half that shown in Figs. 9 and 12.

3. The following formulas for the equivalent reactance are recommended for general use.

For either the cylindrical-rotor or salient-pole condenser,

$$x_{eq} = x_l + \frac{x_d - x_l}{k\left(1 + \frac{a}{b}\right)} \tag{19}$$

For a cylindrical-rotor motor or generator operating at ordinary motor and generator power factors,

$$x_{eq} \cong x_l + \frac{x_d - x_l}{k\sqrt{1 + \frac{a}{b}}} \tag{20}$$

For salient-pole motors and generators operating at normal power factors,

$$x_{eq} \cong x_l + \frac{x_d - x_l}{\left[k_1\left(1 + \frac{a_1}{2b_1}\right) + k_2\left(1 + \frac{a_2}{b_2}\right) - 1\right]} \tag{21}$$

In those cases where the system constants are known, a more exact determination of the equivalent reactance for motors and generators may be made by the methods described in this paper. Equation 19 for synchronous condensers is exact and independent of the connected system.

Appendix A—Determination of ∂k/∂e

Figure 2 contains a saturation curve *OPN* showing the relation between the voltage e_l, and the mmf ke_l necessary to produce this voltage under load conditions, holding a constant value of field excitation e_d. Let P be the operating point on this load saturation curve. Then for small changes in voltage, the saturation curve may be approximated by the straight line *RPS*, tangent at the point P.

Then, from similar triangles *PQS* and *PTR*,

$$\frac{QS}{QP} = \frac{TR}{TP} \tag{A-1}$$

or

$$\frac{\Delta(e_l)}{\Delta(ke_l)} = \frac{b}{ke_l} \tag{A-2}$$

which gives

$$ke_l\Delta(e_l) = b\Delta(ke_l) \tag{A-3}$$

$$= bk\Delta(e_l) + be_l\Delta(k) \tag{A-4}$$

Simplifying

$$\frac{\Delta(k)}{\Delta(e_l)} = \frac{k(e_l - b)}{be_l} = \frac{ka}{e_lb} \tag{A-5}$$

Therefore

$$\frac{\partial k}{\partial e_l} = \frac{ka}{e_lb} \tag{A-6}$$

Similar expressions to eq A-6 apply for the salient-pole case, that is,

$$\frac{\partial k_1}{\partial e_l} = \frac{k_1a_1}{e_lb_1} \tag{A-7}$$

and

$$\frac{\partial k_2}{\partial e_{ld}} = \frac{k_2a_2}{e_{ld}b_2} \tag{A-8}$$

where

$$k_1 = 1 + \frac{\text{iron mmf in the stator}}{\text{air gap mmf}} \qquad k_2 = 1 + \frac{\text{iron mmf in the rotor}}{\text{air gap mmf}}$$

Appendix B—Determination of x_{eq} for a Cylindrical-Rotor Synchronous Machine

Equations 3 and 4 may be written as follows:

$$-\left[i(x_d - x_l)^2 + ke_l(x_d - x_l)\sin\phi\right] = \left[ke_l + i(x_d - x_l)\sin\phi\right]$$
$$\left[1 + \frac{a}{b}\right]\left[k\right]\frac{de_l}{di} + \left[ke_li(x_d - x_l)\cos\phi\right]\frac{d\phi}{di} \tag{B-1}$$

$$-\left[i(x_{eq} - x_l)^2 + e_l(x_{eq} - x_l)\sin\phi\right] = \left[e_l + i(x_{eq} - x_l)\sin\phi\right]\frac{de_l}{di}$$
$$+ \left[e_li(x_{eq} - x_l)\cos\phi\right]\frac{d\phi}{di} \tag{B-2}$$

A third relation between $\frac{de_l}{di}$, $\frac{d\phi}{di}$, and x_{eq} which is dependent on the connected system is necessary in order to determine x_{eq} which may be determined with sufficient accuracy for most cases if the remaining machines of the system are considered as one equivalent synchronous machine. Any shunt impedance may be combined with the equivalent receiving system into an equivalent synchronous machine as has previously been demonstrated.[5] This results in the machine under consideration being connected directly by a series impedance $(r_e + jx_e)$ to an equivalent synchronous machine.

The expression for the voltage e_e of the equivalent system is

$$e_e = \sqrt{(e_l)^2 + i^2\left[(r_a + r_e)^2 + (x_l + x_e)^2\right] - 2ie_l \overline{\left[(x_l + x_e)\sin\phi + (r_a + r_e)\cos\phi\right]}} \tag{B-3}$$

For small changes and $de_e = 0$,

$$-\left[i(r_a + r_e)^2 + i(x_l + x_e)^2 - e_l(x_l + x_e)\sin\phi - e_l(r_a + r_e)\cos\phi\right] =$$
$$\left[e_l - i(x_l + x_e)\sin\phi - i(r_a + r_e)\cos\phi\right]\frac{de_l}{di}$$
$$-\left[ie_l(x_l + x_e)\cos\phi - ie_l(r_a + r_e)\sin\phi\right]\frac{d\phi}{di} \tag{B-4}$$

Equations B-1, B-2, and B-4 may be solved simultaneously for any particular case in order to determine the approximate value of x_{eq}. This value of x_{eq} then can be used to determine the steady state characteristics of the machine for any particular assumed load condition.

Appendix C—Equivalent Reactance of Salient-Pole Synchronous Machine

From the vector diagram of Fig. 3,

$$e_d = (k_1 + k_2 - 1)e_{ld} + (x_d - x_l)i_d \tag{C-1}$$

k_1 is a function of e_l and k_2 is a function of e_ld. Therefore, for small changes equation C-1 yields,

$$de_d = \left(k_1 + k_2 - 1 + e_{ld}\frac{\partial k_2}{\partial e_ld}\right)de_{ld} + e_{ld}\frac{\partial k_1}{\partial e_l}de_l$$
$$+ \left(x_d - x_l\right)di_d \tag{C-2}$$

Since

$$e_{ld} = e_l\cos\beta \tag{C-3}$$

$$de_l = \sec\beta\, de_{ld} + e_l\tan\beta d\beta \tag{C-4}$$

Substituting equation C-4 and letting $de_d = 0$ in equation C-1

$$\frac{de_{ld}}{di_d} = -\frac{(x_d - x_p) + e^2_l \sin\beta \dfrac{\partial k_1}{\partial e_l}\dfrac{d\beta}{di_d}}{\left[k_1 + k_2 - 1 + e_{ld}\dfrac{\partial k_2}{\partial e_l d} + e_l \dfrac{\partial k_1}{\partial e_l}\right]} \tag{C-5}$$

Since from Appendix A

$$\frac{\partial k_1}{\partial e_l} = \frac{a_1}{b_1}\frac{k_1}{e_l} \text{ and } \frac{\partial k_2}{\partial e_{ld}} = \frac{a_2}{b_2}\frac{k_2}{e_{ld}} \tag{C-6}$$

equation C-5 becomes

$$\frac{de_{ld}}{di_d} = -\frac{(x_d - x_l) + \dfrac{k_1a_1}{b_1} e_l \sin\beta \dfrac{d\beta}{di_d}}{\left[k_1\left(1 + \dfrac{a_1}{b_1}\right) + k_2\left(1 + \dfrac{a_2}{b_2}\right) - 1\right]} \tag{C-7}$$

Therefore

$$x_{d(eq)} = x_l + \frac{(x_d - x_l) + \dfrac{k_1a_1}{b_1} e_l \sin\beta \dfrac{d\beta}{di_d}}{\left[k_1\left(1 + \dfrac{a_1}{b_1}\right) + k_2\left(1 + \dfrac{a_2}{b_2}\right) - 1\right]} \tag{C-8}$$

The second term of the numerator of eq C-8 gives the variation of the equivalent direct axis reactance with change in the connected system. However, at $\beta = 0$ or $d\beta = 0$, the conditions for a synchronous condenser,

$$x_{d(eq)} = x_l + \frac{x_d - x_l}{\left[k_1\left(1 + \dfrac{a_1}{b_1}\right) + k_2\left(1 + \dfrac{a_2}{b_2}\right) - 1\right]} \tag{C-9}$$

Equation C-9 is the equation for the equivalent direct axis reactance of a salient-pole synchronous condenser and corresponds to eq 5 derived for the cylindrical-rotor case, since

$$k = k_1 + k_2 - 1$$

and

$$k\frac{a}{b} = k_1\frac{a_1}{b_1} + k_2\frac{a_2}{b_2}$$

when $e_l = e_{ld}$.

The value of $x_{d(eq)}$ may be determined at $\beta = 90°$, also independent of the connected system by making use of the following relation.

$$e_d = e_l \cos\beta + [x_{d(eq)} - x_l]\, i_d \tag{C-10}$$

Equation C-10 for small changes and $de_d = 0$ gives,

$$e_l \sin\beta \frac{d\beta}{di_d} = [x_{d(eq)} - x_l] + \cos\beta \frac{de_l}{di_d} \tag{C-11}$$

Substituting C-11 in C-8 and solving for $x_{d(eq)}$

$$x_{d(eq)} = x_l + \frac{x_d - x_l + \dfrac{k_1a_1}{b_1}\cos\beta \dfrac{de_l}{di_d}}{\left[k_1 + k_2\left(1 + \dfrac{a_2}{b_2}\right) - 1\right]} \tag{C-12}$$

Equation C-12 is an alternative expression for $x_{d(eq)}$ which for $\beta = 90°$ or $de_l = 0$ gives

$$x_{d(eq)} = x_l + \frac{x_d - x_l}{\left[k_1 + k_2\left(1 + \dfrac{a_2}{b_2}\right) - 1\right]} \tag{C-13}$$

Equations C-9 and C-13 indicate the range of values that are obtainable from $d\beta = 0$ to $de_l = 0$. An approximate expression for $x_{d(eq)}$ for the usual motor and generator angles and external impedance can be obtained by taking the arithmetical mean of these 2 equations. (Fig. 11.)

$$x_{d(eq)} \cong x_l + \frac{x_d - x_l}{\left[k_1\left(1 + \dfrac{a_1}{2b_1}\right) + k_2\left(1 + \dfrac{a_2}{b_2}\right) - 1\right]} \tag{C-14}$$

In Fig. 4 $e_{(eq)}$ is a voltage maintained constant in magnitude for the particular load conditions for which $x_{d(eq)}$ and $x_{q(eq)}$ were determined.

Appendix D—$x_{d(eq)}$ and $x_{q(eq)}$ for Salient-Pole Machines With External Impedance

From the vector diagram of Fig. 3 for the salient-pole machine,

$$e_d = (k_1 + k_2 - 1)\, e_{ld} + (x_d - x_l)\, i_d \tag{D-1}$$

$$e_q = -k_1 e_{lq} + (x_q - x_l)\, i_q \tag{D-2}$$

While for the external system,

$$e_{ld} - e_e \cos\delta = i_q(r_e + r_a) + i_d(x_e + x_l) \tag{D-3}$$

$$-e_{lq} + e_e \cos\delta = i_q(x_e + x_l) - i_d(r_e + r_a) \tag{D-4}$$

Also,

$$x_{d(eq)} = x_l - \frac{de_{ld}}{di_d} \tag{D-5}$$

$$x_{q(eq)} = x_l + \frac{de_{lq}}{di_q} \tag{D-6}$$

Differentiating eqs D-1, D-2, D-3, and D-4, letting de_d and $de_e = 0$ and solving for de_{ld}/di_d and de_{lq}/di_q and substituting in D-5 and D-6, the general expressions for $x_{d(eq)}$ and $x_{q(eq)}$ are obtained in terms of the external impedance $r_e + jx_e$.

$$x_{d(eq)} = x_l + \frac{\begin{gathered}-h(x_d - x_l)\,[(r_a + r_e)\cos\delta - (x_l + x_e)\sin\delta] \\ +g(x_q - x_l)\,[(x_l + x_e)\cos\delta + (r_a + r_e)\sin\delta] \\ +(x_d - x_l)(x_q - x_l)\sin\delta\end{gathered}}{\begin{gathered}(fh - g^2)\,[(x_l + x_e)\sin\delta - (r_a + r_e)\cos\delta] \\ (f\sin\delta - g\cos\delta)(x_q - x_l)\end{gathered}} \tag{D-7}$$

$$x^q{}_{(eq)} = x_l + \frac{\begin{gathered}f(x_q - x_l)\,[(x_l + x_e)\cos\delta + (r_a + r_e)\sin\delta] \\ +g(x_d - x_l)\,[(x_l + x_e)\sin\delta - (r_a + r_e)\cos\delta] \\ +(x_d - x_l)(x_q - x_l)\cos\delta\end{gathered}}{\begin{gathered}(fh - g^2)\,[(x_l + x_e)\cos\delta + (r_a + r_e)\sin\delta] \\ (h\cos\delta - g\sin\delta)(x_d - x_l)\end{gathered}} \tag{D-8}$$

Where

$$f = k_1 + k_2 - 1 + \frac{a_1}{b_1}k_1\cos^2\beta + \frac{a_2}{b_2}k_2$$

$$g = \frac{a_1}{2b_1}k_1 \sin 2\beta$$

$$h = k_1 + \frac{a_1}{b_1}k_1\sin^2\beta$$

Figure 11 is a plot of D-7 and D-8 for the equivalent direct and quadrature axis reactances of a salient-pole generator operating at rated kilovoltamperes and rated (0.8) power factor with varying amounts of external resistance and reactance.

Appendix E—x_{eq} for a Cylindrical-Rotor Synchronous Machine at Constant Power Factor

The differential equation, eq 3, of a saturated machine for small and gradual changes with constant field excitation may be written as follows,

$$\begin{aligned}0 = {} & \left[ke_l + i(x_d - x_l)\sin\phi\right]\left[1 + \frac{a}{b}\right]k\frac{de_l}{di} \\ & + [ke_l i(x_d - x_l)\cos\phi]\frac{d\phi}{di} \\ & + [i(x_d - x_l)^2 + ke_l(x_d - x_l)\sin\phi]\end{aligned} \tag{E-1}$$

Using the relations,

$$e_l = \sqrt{(e_t\cos\theta)^2 + (e_t\sin\theta + ix_l)^2}$$

$$\sin\phi = \frac{e_t\sin\theta + ix_l}{e_l}$$

$$\cos\phi = \frac{e_t \cos\theta}{e_t}$$

letting $d\theta = 0$ (constant power factor) and rearranging,

$$\frac{de_t}{di} = -\frac{\left\{\begin{array}{l}\frac{e_t}{i}\sin\phi\left[1 + k\left(1+\frac{a}{b}\right)\frac{x_l}{(x_d - x_l)}\right] \\ + x_l + \frac{x_d - x_l}{k} + \frac{a}{b}x_l \sin^2\phi\end{array}\right\}}{\left\{\begin{array}{l}\frac{e_t}{i}[\cos(\phi-\theta)]\,k\left(1+\frac{a}{b}\right)\left(\frac{1}{x_d - x_l}\right) \\ + \sin\theta + \frac{a}{b}\sin\phi\cos(\phi-\theta)\end{array}\right\}} \quad \text{(E-2)}$$

For unity power factor, eq 2E, reduces to

$$\frac{de_t}{di} = -\frac{\left\{\begin{array}{l}x_l\left[1 + k\left(1+\frac{a}{b}\right)\left(\frac{x_l}{x_d - x_l}\right)\right] \\ + x_l + \frac{x_d - x_l}{k} + \frac{a}{b}x_l\frac{i^2x_l^2}{e_t^2 + i^2x_l^2}\end{array}\right\}}{\left\{\begin{array}{l}\frac{e_t}{i}k\left(1+\frac{a}{b}\right)\frac{1}{x_d - x_l} \\ + \frac{a}{b}\left(\frac{e_tix_l}{e_t^2 + i^2x_l^2}\right)\end{array}\right\}} \quad \text{(E-3)}$$

While for zero power factor

$$\frac{de_t}{di} = -\left[x_l + \frac{x_d - x_l}{k\left(1+\frac{a}{b}\right)}\right] \quad \text{(E-4)}$$

Substituting $k = 1$, $\frac{a}{b} = 0$ and $xd = x_{eq}$ in eq E-2, the following expression is obtained for the equivalent unsaturated machine at constant power factor,

$$\frac{de_t}{di} = -\frac{x_{eq}\left(\frac{e_t}{i}\sin\theta + x_{eq}\right)}{\left(\frac{e_t}{i} + x_{eq}\sin\theta\right)} \quad \text{(E-5)}$$

or

$$x_{eq} = -\left(\frac{de_t}{di} + \frac{e_t}{i}\right)\frac{\text{sine }\theta}{2} + \sqrt{\left(\frac{de_t}{di} + \frac{e_t}{i}\right)^2\left(\frac{\sin\theta}{2}\right)^2 - \frac{de_t}{di}\cdot\frac{e_t}{i}} \quad \text{(E-6)}$$

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Rocking Indirect Arc Electric Furnaces

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The electric furnace of the rocking type with indirect arc has been developed to the point where it may be used not only for the melting of nonferrous metals but also in the production of castings of various types of iron and steel. Accurate control of the process is possible. Many new cast irons may thus be produced with qualities greatly superior to the cast iron which may be produced by any other means.

DURING the past 25 years the electric melting furnace has developed from the position of a very interesting experimental apparatus to that of a precise, highly dependable, thoroughly practicable device for the melting of a wide variety of metals under prescribed conditions and producing molten metal precisely conforming with both the predetermined desired chemical analysis and correct degree of temperature.

Various methods have been employed and several types of furnaces have been developed for the purpose of utilizing electric energy as a source of heat for melting metals. It is the purpose of this paper to trace the development and describe the design, operation, and utilization of the rocking indirect arc electric furnace. This furnace, first marketed in 1918, has become widely used, first in nonferrous metal melting and later in the production of castings of gray iron, malleable iron, heat treated cast iron, and alloy iron and steel.

The furnace, which is of the single-phase 2-electrode indirect-arc type, shows excellent electrical regulation and very satisfactory power-factor conditions. The metal stirring action of this furnace, together with its deoxidizing atmosphere and accurate temperature control at elevated tempera-

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tures, afford an excellent implement for the production of the many new varieties of cast iron, heat treated iron, and alloy iron now receiving acute interest from metallurgists and design engineers. It is similarly receiving the intense interest of central stations and electrical equipment manufacturers as a builder of a substantial volume of new business in a heretofore uncultivated field for electrification.

DESIGN

Many varying designs of stationary indirect arc furnaces were built both in this country and abroad shortly after the beginning of the twentieth century, but the difficulties encountered with electrical, mechanical, and refractory problems apparently precluded the commercial development of any of these designs to the point of general industrial utilization.

During the World War the imperative necessity of a rapid melting medium for the production of brass and bronze castings stimulated the development of the electric furnace for such purposes and it was at that time that the rocking indirect arc electric furnace was designed and developed as a commercially adaptable machine.

This furnace is of the horizontally cylindrical type with 2 electrodes, these being inserted from opposite ends at the axis of the furnace. The furnace is lined with high temperature refractories and a charging door and pouring spout are provided upon the side of the cylinder to effect easy manipulation. The furnace is carried upon a ring track which is supported by 4 rollers and the oscillating or rocking movement is imparted to the furnace cylinder either by friction drive through the rollers or, as in the larger sizes, by means of ring gears and spur gears arranged coaxially with the ring tracks and rear rollers, respectively. The 2 types of drive are shown in the furnaces illustrated in Figs. 1 and 2.

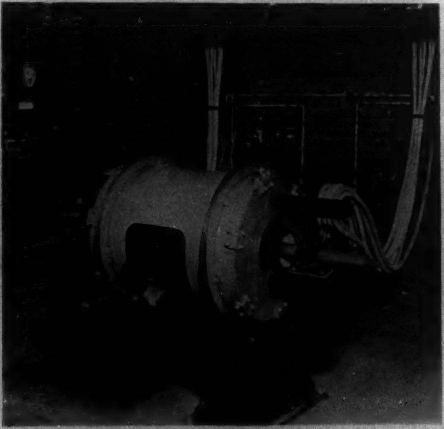

Fig. 1. A rocking indirect arc electric melting furnace. This is a 350-lb 125-kw unit with friction drive through supporting rollers

Fig. 2. Rocking of this 3,000-lb 600-kw furnace is obtained with ring gear drive

An electric motor of requisite size is mounted upon the furnace base, this motor being controlled by a reversing switch actuated, through gears, by the furnace shell, the switch being so designed that the index or control levers upon the switch face plate correspond with the extreme positions of the pouring spout. In this way the operator may readily adjust the angle of rock or oscillation, it being only necessary to adjust the reversing switch index levers to the space or angle desired. This same switch is employed as a hand operated drum type controller while the molten metal is being poured and the switch design provides a control of the metal stream sufficiently precise to permit the accurate pouring of any amount of metal required even to the so-called "shrinking" of billets, ingots, or bars, when pouring into metallic molds.

Current is carried from suitably arranged bus bars to the water-cooled electrode clamps by means of flexible apparatus cable, this cable being covered with flame-proof insulation. The electrodes are adjustably mounted and their adjustment may be effected by either hand or automatic electrically operated control mechanism, as may be desired.

Suitable indicating meters and a special integrating kilowatthour meter are arranged for proper power input control, the rate of energy input being adjusted by controlling the distance between the 2 electrodes and thus the length of the arc. Obviously the arc is maintained at the center of the furnace and only one electrode need be adjusted during the "heat" or melting cycle, the nonoperating electrode being moved inward between heats to compensate for its consumption, input control being effected by occasional adjustment of the opposite electrode during the heat.

A single-phase furnace transformer of special design is employed, the high voltage winding being adapted to whatever power supply service may be available and the low voltage open-circuit potential may vary between 90 and 130 volts, depending upon the furnace capacity and the metal to be melted.

Suitable voltage taps, both above and below normal, are provided in the high voltage winding, and a reactor, for arc stabilization purposes, with variable taps for changing reactance values, is built within the transformer case, being mounted above the transformer coils. The amount of reactance required varies according to the regulation of the power supply circuit and according to the metal being melted. By the latter it is meant that when melting a metal which volatilizes at a relatively low temperature, thus introducing excessive metallic vapor into the furnace atmosphere, the arc impedance is lower and the arc is less stable so that a relatively lower furnace voltage and higher reactance is necessary than when melting nonvolatile metals such as iron. A typical layout plan illustrating the relative arrangement of the furnace, the transformer, and control apparatus is shown in Fig. 3.

The furnace is lined either with refractory shapes or with a monolithic rammed plastic refractory, the former usually being more satisfactory because of the technique required and difficulty often encountered in properly installing a rammed monolithic refractory material. The rapid commercial development of high temperature refractories during the past 5 years has produced a wide variety of available refractory materials, adaptable to various metallurgical operations with facility and economy previously unattainable.

OPERATION—
CONNECTIONS AND ELECTRICAL CONTROL

It is of course desirable to install the transformer as close to the furnace as is practicable in order to avoid long low voltage conductors, and these conductors should be interlaced from the transformer terminals to a point near the furnace where they are segregated for the purpose of connecting the flexible furnace cables.

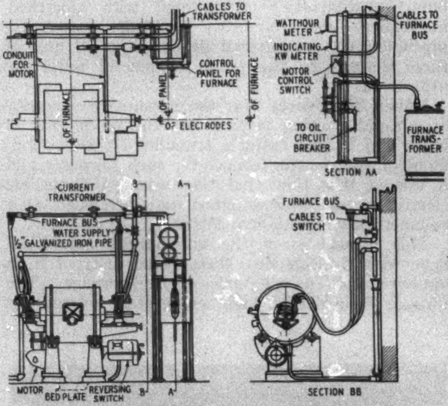
CABLES TO TRANSFORMER
CONDUIT FOR MOTOR
CONTROL PANEL FOR FURNACE
OF PANEL
OF FURNACE
OF FURNACE
OF ELECTRODES
WATTHOUR METER
INDICATING KW METER
MOTOR CONTROL SWITCH
TO OIL CIRCUIT BREAKER
CABLES TO FURNACE BUS
FURNACE TRANSFORMER
SECTION AA
CURRENT TRANSFORMER
FURNACE BUS
WATER SUPPLY
½" GALVANIZED IRON PIPE
B
A
MOTOR
BED PLATE
REVERSING SWITCH
B
A
FURNACE BUS
CABLES TO SWITCH
SECTION BB

Fig. 3. Typical installation print showing relative positions of furnace, control panel, and transformer

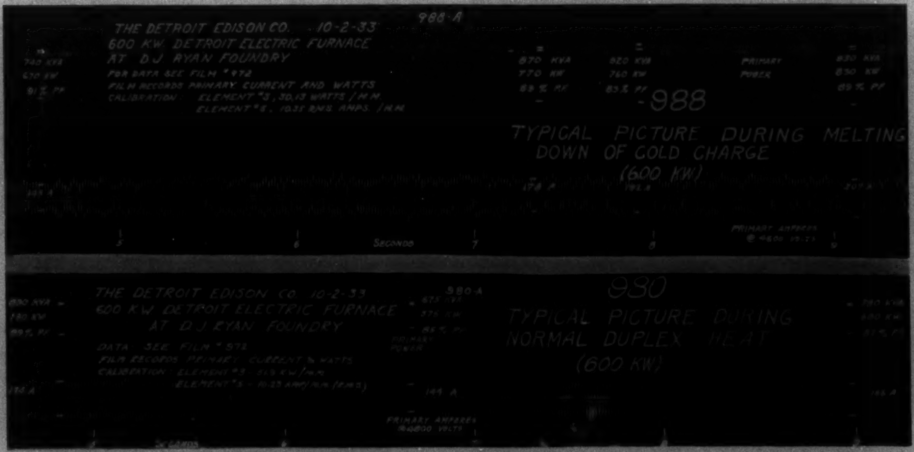

Fig. 4. Oscillographic records of a 600-kw unit

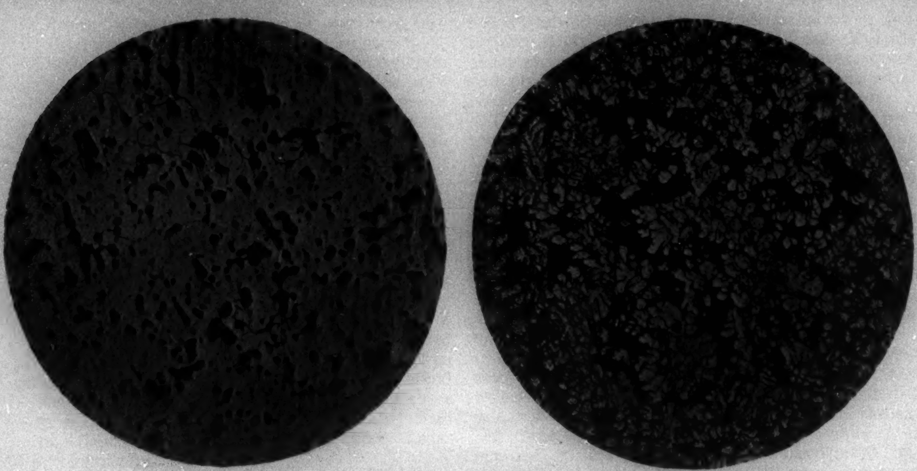

Fig. 5. Photomicrographs illustrating markedly uniform microstructure. Both etched, and magnified approximately 75 diameters

(Left). Leaded bearing liner. 78 per cent copper, 16 per cent lead
(Right). Piston packing. 60 per cent lead

The transformer voltage and reactance taps are connected for the desired energy input and arc stability. The nonoperating electrode is moved into the furnace so that its inner end projects about 2 in. beyond the center line of the furnace. The operating or controlling electrode is then moved in until contact is made and the arc established. The instantaneous rush of current occurring when striking the arc will, in a properly installed furnace, reach a value of approximately twice the transformer rated current capacity. Since the transformer is usually connected to the 20 per cent reactance tap this impedance together with that of the entire low voltage circuit, including furnace inductance and inherent arc impedance, precludes any value greater than from 2 to $2^1/_2$ times normal operating current. If it is desirable to hold the fluctuation or current surge to lower values than these, this may be very readily accomplished by inserting an additional reactor in circuit when starting a cold furnace, very simple switching equipment being provided for short-circuiting this reactor after the arc has been in operation for a few minutes.

The average power factor at the high voltage terminals of the furnace transformer, after the furnace is heated up and in regular operation, should be not less than 0.80. Many carefully installed furnaces, where close attention has been paid to arrangement of conductors, as well as to the correct adjustment of voltage and reactance taps, have shown an actual average high voltage power factor of between 0.85 and 0.90. Oscillographic records of the current and voltage on a 600-kw furnace load are shown in Fig. 4.

The electrical regulation of the indirect arc type furnace is obviously materially better than that of the direct arc type. The arc, being sustained between the 2 electrodes, does not swing or fluctuate as often or as widely as when the arc is between the electrode and the metal charge, as is the case in any direct arc furnace. In such a direct arc, the fluctuations are very frequent and very broad, either during the melting period when the arc is playing upon the rapidly varying contour of the cold scrap charge, or later when the arc is very short and plays upon the surface of boiling metal.

In the indirect arc furnace neither the physical character of the charge nor the condition of the bath has any effect upon the arc regulation, and for these reasons this type of furnace offers a much simpler problem to the electrical engineer, as well as to the furnace user, whose operating problems are sufficiently difficult without the added complications of an unnecessarily intricate electrical mechanism.

Due to the rapid metallurgical development in the iron and steel industry, the wide adoption of alloyed materials and the wide diversity of analyses resulting from this practice, the present tendency both here and abroad is toward a greater number of relatively smaller furnaces instead of toward the concentration of operation in a single unit. This movement effects a higher diversity factor and improved load factor, and consequently an improved operating efficiency with lower power costs. The indirect arc type furnace, because of its relatively simple design and construction, its flexibility and ease of operation, and its effective metallurgical performance lends itself admirably to the modern trend of the metal industry.

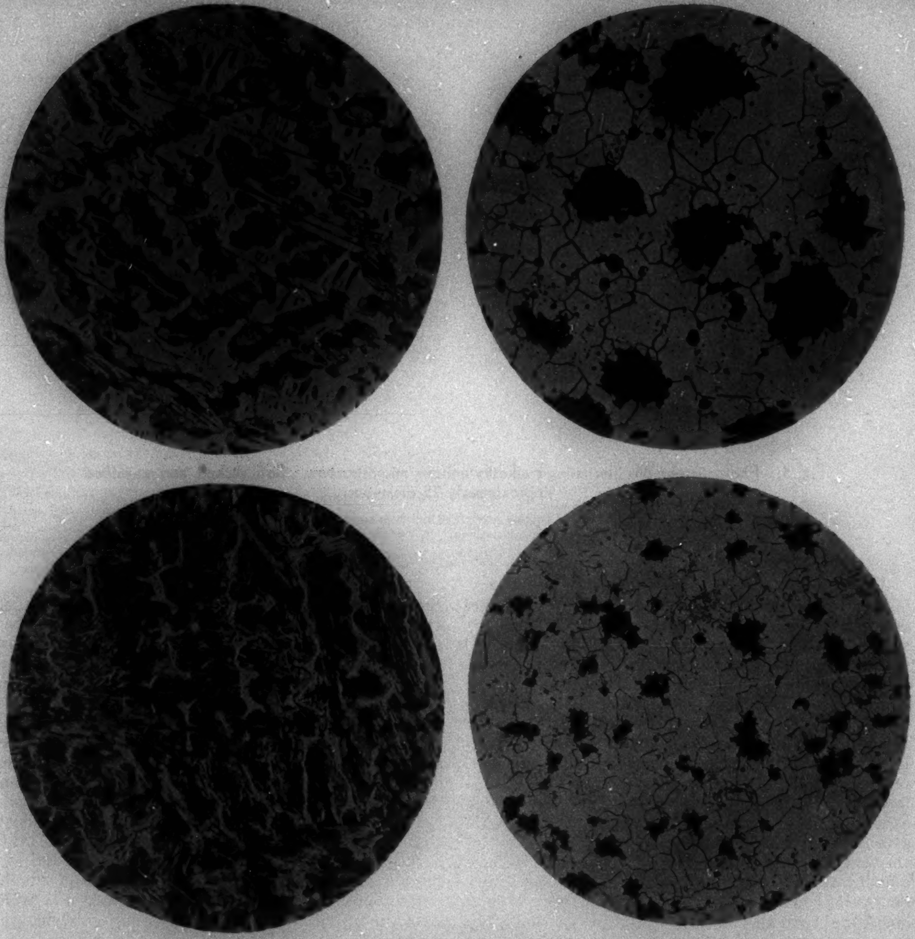

Fig. 6. Photomicrographs showing structures of air furnace iron (above) compared with iron produced in the rocking indirect arc electric melting furnace (below). All 4 photomicrographs etched, and magnified approximately 125 diameters

(Left, above). Air furnace white iron. 2.5 per cent carbon
(Right, above). The same iron annealed, approximately 140-hr cycle. Tensile strength 55,000 lb per square inch
(Left, below). White iron produced in rocking indirect arc electric melting furnace. 2.5 per cent carbon
(Right, below). Same iron annealed, 20-hr cycle. Tensile strength 62,000 lb per square inch

Deoxidizing Atmosphere

The indirect arc furnace inherently possesses a deoxidizing atmosphere, due to the prevalence of carbon monoxide gas liberated through the reaction of the incandescent electrodes and the arc itself. Such an atmosphere precludes the metallic losses ordinarily encountered in other types of melting furnaces. When melting charges containing expensive alloying elements such as chromium, nickel, vanadium, these losses in other furnaces often amount to a cost higher than the entire actual furnace melting or conversion cost. In the melting of nonferrous alloys, such as brass or bronze, the indirect arc furnace ordinarily shows a net metallic loss in the actual melting operation of only 10 to 25 per cent of the losses involved in the operation of the fuel fired furnaces which they have supplanted.

This saving of metals as well as of operating cost is of vital importance to industry and to society.

Where an oxidizing or other controlled atmospheric condition is desired, air or other gases may be very readily and easily introduced into this type of furnace under precise control, and this feature of this type of furnace has been found valuable to many users.

TEMPERATURE CONTROL

The energy input to this furnace is integrated by an especially designed meter equipped with a 4-in. dial, so calibrated that the power used may be read to within 1 or 2 kilowatthours. The quantity of metal in the furnace being known, the rate of power input being uniform over any predetermined time, and the radiation loss being constant, molten metal temperature determinations by this method are very apt to be much more accurate than those made with ordinary precaution by any other than an experienced operator using the ordinary forms of pyrometric instruments.

In fact, many concerns requiring precision temperature control find that a charted calculation of kilowatthours input into a charge in a given period of time affords the most satisfactory form of temperature control, a pyrometer being only occasionally used for checking purposes.

ROCKING ACTION

In the type of furnace described in this paper, undoubtedly the most outstanding characteristic is its rocking action. The principal design function of this action is to effect homogeneity of the constituents of the charge. Fifteen years of commercial usage have proved the effectiveness of this type of furnace in this respect to beyond any point of argument. In Fig. 5 is illustrated a high lead bearing mixture with which considerable segregation difficulty is ordinarily experienced. The markedly uniform microstructure will be noted.

When the charge is first placed in the furnace and the arc is established, the furnace is started rocking through an angle of about 15 deg. As melting progresses this angle is successively increased until, when the charge is completely molten, the charging door moves from metal level to metal level upon the opposite sides, or through an angle of approximately 200 deg. This full rocking action, which occurs at the rate of 2 cycles per minute, is maintained during the superheating period and is directly responsible for several highly beneficial effects.

This movement produces a thoroughly mixed homogeneous molten bath. It facilitates complete degasification of the metal and insures freedom from occluded slag particles. In melting iron this rocking action at the elevated metal temperatures employed, expedites the solution of carbon and the breaking down of carbides. It effects a diffusion of nucleuses throughout the metal as poured which affords a brief path of graphite migration when this element is precipitated either as the casting cools or in any subsequent heat treating process. In Fig. 6 is illustrated a comparison of air furnace iron and rocking electric furnace iron of identical chemical characteristics. The improvement in microstructure and physical characteristics shown is obviously the result of the rocking action at high temperature.

The automatically controlled rocking action permits the use of charges containing 100 per cent borings and turnings which, while they consist of excellent metallurgical quality, are nevertheless the cheapest form of metal on the market, being almost unsalable in many localities. These materials are thoroughly adaptable to the production of the highest types of castings when melted in this type of electric furnace. Several castings of various usage made from charges consisting entirely of borings are illustrated in Fig. 7. This is an economic advantage distinctly peculiar to this type of furnace.

This rocking action increases the melting speed since the charge is heated not only by direct and reflected radiation, but by conduction as well, the metal picking up from the refractory walls the excess heat absorbed by the refractory while it is exposed to the arc. It will be recognized immediately that this reaction must effect improved thermal efficiency since it involves the transmission of refractory heat to the metal charge instead of through the refractory to be lost to the surrounding atmosphere. This insures lower power consumption.

By this means, also, the refractory lining is kept within a relatively narrow range of temperature rise above that of the metal, and because of this lower temperature is subject to less punishment by fusion or erosion than it would be if its temperature were intensely increased by more continuous exposure to radiation from the electric arc, as would be the case in a stationary furnace. The effectiveness of this function is evidenced in the relatively low refractory cost in this furnace when compared with others doing similar work.

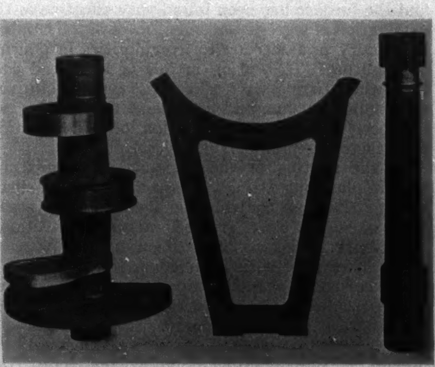

Fig. 7. Castings made from electric furnace charge consisting entirely of borings

Contingent upon this excellent refractory performance is another important matter. The freedom from excessive refractory temperatures and consequent fusion of linings is partially responsible for the remarkable control of analysis obtained when melting in this furnace. In other types of furnaces uncontrollable silicon or other chemical pick-up is regularly experienced due to the fusion of linings which introduces undesirable reaction in the metal bath. The advantage of this type of furnace in avoiding such contamination is of great commercial importance.

Since the electrode consumption of the electric arc furnace is a function of the energy consumed, granting ordinarily good mechanical structure, it also becomes apparent that the furnace which uses a lower amount of power in melting should consume a correspondingly less amount of electrodes.

UTILIZATION

It then seems evident that the indirect arc rocking electric furnace should be an attractive melting medium in the ferrous and nonferrous fields from the standpoints of economy of operation, simplicity in performance, ease in manipulation, assurance of desired control, and quality of product. Let us for a moment study its field of use and the attendant results.

Hundreds of these furnaces are in use in this country and abroad in brass and bronze foundries of every variety. In the melting of such alloys the homogeneity and temperature control afforded by this type of furnace are of extreme importance, and the furnace has been found very effective in the elimination of segregation and of most of the troubles in foundry practice due to irregularities in pouring temperature. In bearing metals of high lead content, the stirring action of this type of furnace is of unusual value, and because of this the furnace has been the means of solution of many critical manufacturing problems in several plants.

In the melting of the various bronze mixtures used in plumbing fittings, pressure goods, and steam fittings, the close control of analysis and the assurance of dense, close grained metal is of utmost importance. The rocking action of this type of furnace, together with its freedom from oxidization and excessive local high temperatures in the molten metal, facilitates the production of a very superior casting with excellent economy.

In the production of alloy steel castings, and especially in the remelting of alloy steel scrap containing chromium, nickel, and other expensive alloys, the precise analytical control, the accurate control of temperature, and the complete recovery of alloy materials experienced in the use of the rocking indirect arc electric furnace, prove to be of extreme value to the many concerns employing them for this purpose.

Perhaps the most important application of this furnace is in its most recent adaptation to the iron foundry. During the past 3 years over 90 of these furnaces have been put to work in foundries producing gray iron castings, various types of malleable and heat treated iron, and alloy iron.

Only 5 years ago the use of cast iron in such form as an automotive crankshaft or camshaft would have been considered preposterous. Today thousands of automobiles are in service in which such shafts are made of cast iron, and the entire automotive industry is intensively studying the engineering and economic feasibility of the substitution of properly designed cast iron for scores of parts which heretofore have been produced as steel forgings or steel castings.

In the railway industry, the electrical industry, the production of automatic machinery, and scores of other important trades the many advantages of a precisely produced cast iron have been the means of not only lowering the cost of production but of simultaneously improving the product.

Five years ago ordinary cast iron was considered as a material possessing tensile strength of from 20,000 to 25,000 lb per square inch, and utterly unfit for use in any application in which dependable engineering design was involved. Today, since the adaptation of the electric furnace to the cast iron field, tons of unalloyed, unheat-treated gray iron are being produced daily, which show 45,000 to 50,000 lb per square inch tensile strength and correspondingly improved transverse strength.

A MAJOR METALLURGICAL AND MECHANICAL ENGINEERING CHANGE

Many concerns are regularly producing heat-treated cast iron showing from 90,000 to 110,000 lb per square inch tensile strength, with an elongation varying between 6 per cent and 2 per cent as may be desired. Such castings show a remarkable shock and fatigue resistance and possess a modulus of elasticity often above 30 million. These startling and somewhat revolutionary characteristics are acknowledged by leading engineers to be of inestimable value to industry. It is the writer's sincere conviction that this rapidly occurring development in the cast iron industry constitutes a major metallurgical and mechanical engineering change.

The highly desirable qualities and precisely controlled characteristics of these new cast irons may be enjoyed to the utmost only when produced in the closely controlled atmosphere and high temperature of the electric furnace.

In the production of such materials the rocking indirect arc electric melting furnace holds a foremost position, and its utilization for such purposes, both in the production of metal and as a source of power load of vast potentialities, is being studied intensely by the engineering and executive authorities of the largest electrical manufacturers of the country, the public utilities, and the metal working industries in general.

It is the writer's belief that before the close of the present decade there will be installed and in use in this country electric iron melting furnaces totaling over 250,000 kw capacity and using over 500,000,000 kwhr to produce approximately 100,000 tons of cast iron annually. The present rate of installation and the character of the interest shown would indicate such an estimate to be conservative.

Protecting Machines From Line Surges

Some of the more important technical problems involved in connecting rotating machines directly to overhead electric power transmission lines are discussed in this paper. Methods are developed for protecting the ground and turn insulations of the armatures of such machines which may be subjected to surge voltages. The ground insulation can be protected by lightning arresters; the turn insulation, by sloping off the incoming surge. Methods are given for determining the maximum allowable rate of rise of voltage at the machine terminals, and the apparatus needed to limit the rate of rise to that value.

By
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IN connecting rotating machines directly to overhead electric power transmission lines, the possibility of surge voltages reaching the armatures of the machines introduces a serious problem. The purpose of this paper is to discuss some of the more important technical phases of that problem and to put part of the problem on a more calculable basis. The real problem has been not so much to name means of protection, but (1) to outline means that could be applied safely and economically and (2) to build up means of predetermining the protection required. In this paper, it is not intended to make *general* recommendations concerning the protection of machines of various voltages and ratings, but rather to furnish means of determining suitable protection for any *specific* machine.

Suitable methods are demonstrated for protecting the ground insulations and the turn insulations of armatures that may be subjected to surge voltages. The test waves used in this investigation were $1\frac{1}{2}$ x 40, $\frac{1}{2}$ x 5, and 10 x 20 μsec. For multiturn coil armature windings, a method is given by which the maximum allowable rate of rise of voltage at the machine terminals may be calculated in terms of the design constants of the winding; in the development of this method of calculation, electromagnetic and electrostatic coupling between turns has been considered. A method also is developed for determining the apparatus necessary to limit the rate of rise of terminal voltage to the desired value. Calculated surge impedance data based on 3 different methods of measurement are given for a 25,000-kva synchronous condenser armature winding.

From the results of this investigation the following conclusions may be reached:

1. The crest voltages of surges that may reach the machine armatures should be limited by lightning arresters at least to the crest value of the 60-cycle test voltage.[8,13]

2. On machines with the same ground insulation throughout, the ground insulation can be protected by lightning arresters regardless of the wave steepness and length for any of the usual winding connections.

3. A machine with graded insulation should be Y-connected and have a grounded neutral (preferably solidly grounded). It can be protected, so far as the ground insulation is concerned, by the proper application of lightning arresters.

4. The turn insulation can be protected by sloping off the incoming wave. The necessary value to which the rate of rise of terminal voltage must be limited can be calculated as outlined in Appendix I. The approximate rate of rise of voltage obtained when certain protective apparatus is used can be calculated as outlined in Appendix II.

5. The surge impedances of the machine when connected in various ways was determined by 3 separate methods of measurement. (See Appendix III.) Substantially the same values were found by 2 of these methods of measurement, and the third gave values of the same order of magnitude. However, these values are all much less in magnitude than those published by other authors for certain other machines. Consequently, it is believed too early to generalize concerning the surge impedances of rotating machines.

6. In all the surge studies on the synchronous condenser used in these tests, the influence of saturation was found to have a small, though measurable, effect. The electromagnetic and electrostatic coupling between phases of this machine, which is of normal design, did not produce important effects. Rotor position did not have an important influence on stator surge voltage distribution. When the rotor was completely removed from the stator, substantially the same voltage distributions in the armature windings were noted during surge tests as before the rotor was removed; but a pronounced difference in the impedance functions for various armature winding connections was observed.

How Surges Penetrate Armature Windings

There are 2 main armature insulations to be protected, the insulation to ground and the insulation

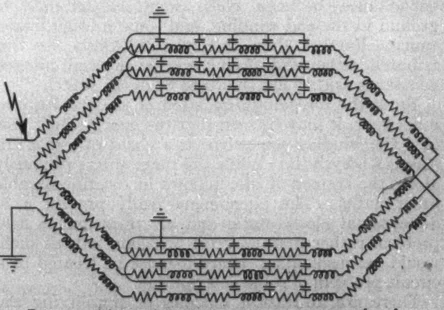

Fig. 1. Network representing approximately the circuit of a multiturn coil armature winding

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Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 23, 1933; released for publication, Nov. 17, 1933. *Not published in pamphlet form.*

8. See bibliography for all numbered references.

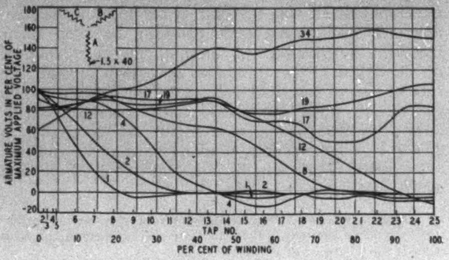


Fig. 2 (above). Y-connected, ungrounded neutral, unprotected

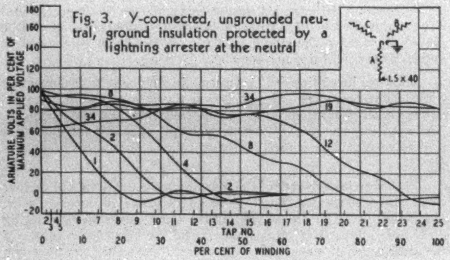


Fig. 3. Y-connected, ungrounded neutral, ground insulation protected by a lightning arrester at the neutral

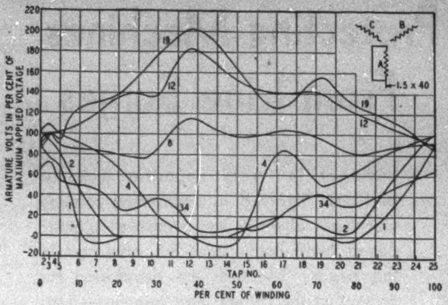


Fig. 4. Δ-connected, unprotected

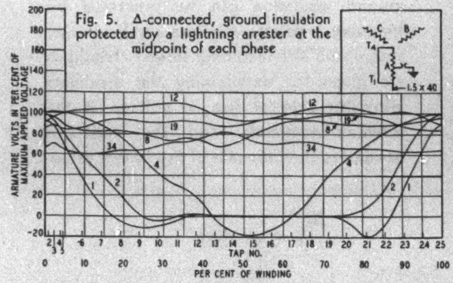


Fig. 5. Δ-connected, ground insulation protected by a lightning arrester at the midpoint of each phase

Figs. 2 to 10, inclusive. Results of surge voltage tests on a 25,000-kva synchronous condenser. The small diagrams show for each set of curves the actual test connections, point of application of surge, and dimensions of wave in microseconds. Numerical designations on the curves indicate the number of microseconds after start of applied wave

between turns. Keeping these in mind, it is desirable to obtain a mental picture of a voltage wave penetrating the armature winding of a rotating machine.

A surge may be thought of as an entering wave of charges all of one sign. The voltage wave produced by these charges may be thought of as a composite of harmonics, several of which are of frequencies higher than 10,000 cycles per second. Consequently, the generator winding should be treated more nearly in its entirety as a complicated network of inductance, resistance, and capacitance than is done in ordinary 60-cycle design or short-circuit studies. A conception of the conditions can be obtained from Fig. 1. In addition to the circuit constants shown, there is capacitance between coils, some capacitance to ground in the end winding, and some mutual inductance. Further than this, the constants are distributed rather than being a series of small lumped constants as they are shown to be in the sketch.

From the foregoing discussion of the armature as a network, it may be seen that the energy must flow into the winding somewhat as a cloud of vapor entering a labyrinth. While the surge enters primarily along the copper, it also billows in by innumerable other paths. The phenomena really present a 3-dimensional electrostatic and electromagnetic field problem rather than a circuit problem, but, as such, would be unsolvable; hence it must be treated as a circuit problem of some description.

There are at least 4 schemes of simplifying the network: (1) treating the machine as one continuous line and neglecting all coupling between turns; (2) treating the machine as an appropriate group of lumped constants; (3) extending scheme 2 by allowing the number of turns to increase without limit; and (4) considering the penetration into the first coil of a multiturn coil winding by assuming it to be similar to a group of parallel lines with one line discontinuous.

Each of these methods should be used only where checks with test data indicate its reliability within the desired range of application. In general, when the machine terminal voltage is increased suddenly and held at a constant value indefinitely, a final steady state voltage distribution is found. This voltage distribution depends on the winding connections and the magnitude of the applied steady voltage. Superposed on this is a decaying oscillating voltage starting in any case so as to produce a very large voltage drop across the terminal coils. This is true regardless of the winding connections.

One question of considerable interest is whether or not the resistance of the machine winding when confronted with a sudden change of voltage is ever likely to be an important damping factor. Numer-

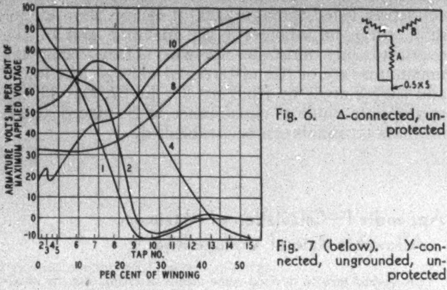
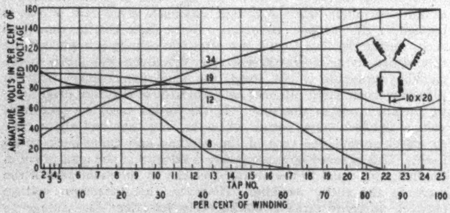


Fig. 6. Δ-connected, unprotected

Fig. 7 (below). Y-connected, ungrounded, unprotected



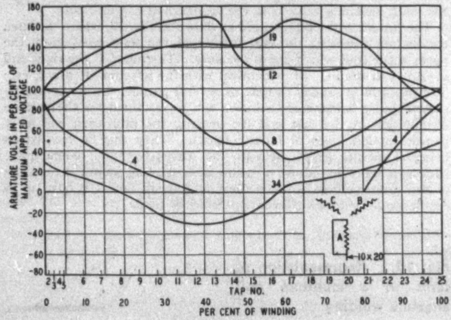


Fig. 8. Δ-connected, unprotected

ous tests with surge generator and cathode ray oscillograph apparatus indicate that it will not. (See figures 2 to 10, inclusive.) From calculations using the measured impedance function (impedance *vs.* frequency) and by treating the machine as a continuous line, the same conclusion may be reached.

Since the damping action of the armature resistance cannot be counted on to prevent severe oscillations within the armature winding, other methods must be considered. In all cases, the terminal voltage must be limited at least to the crest value of the 60-cycle test voltage.[8,13] Where the terminal voltage may exceed this value, a lightning arrester at the machine terminals should be used. This is all that is required to protect the ground insulation of a normally insulated Y-connected machine with a solidly grounded neutral. (Turn insulation will be discussed later.)

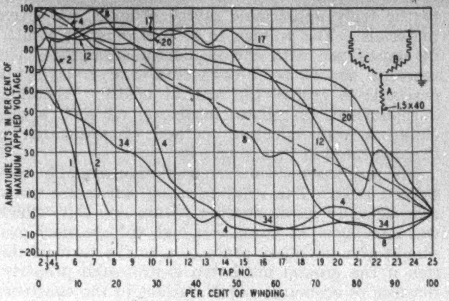


Fig. 9. Y-connected, grounded neutral, unprotected

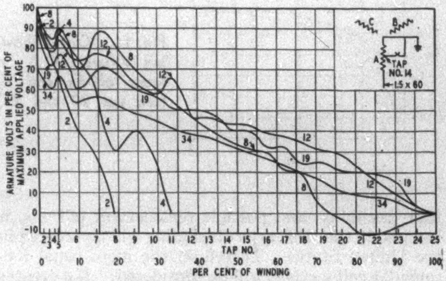


Fig. 10. Y-connected, grounded neutral, ground insulation protected by lightning arresters to permit the use of graded insulation

Effective and economical methods for protecting the ground insulation are demonstrated in Figs. 2, 3, 4, and 5 for 3-phase machines when Y-connected with ungrounded neutral, and when Δ-connected. The applied voltage used in those cases was a $1^1/_2$ x 40-μsec wave. The numbers on each curve indicate the number of microseconds after the start of the applied wave. The data in these curves were obtained on a 25,000-kva synchronous condenser. About 1,000 cathode ray oscillograph films were taken, and these curves are simply summarized material.

It may be well to consider the effects of certain other voltages at the machine terminals, such as $^1/_2$ x 5- and 10 x 20-μsec waves. Results of tests with these waves are shown in Figs. 6, 7, and 8. If waves of both of these latter types are actual possibilities, the general necessity for protection is about the same as for the $1^1/_2$ x 40-μsec wave. Incidentally, $^1/_2$ x 5- and 10 x 20-μsec waves are of the character of those that may reach a rotating machine, even though it be connected to a transmission line through a transformer.

So far, the possibility of grading the insulation to ground has not been considered in this paper. Graded insulation may be very desirable in the design of higher voltage rotating machines, because of the truly appreciable saving of space for active materials. The voltage to ground must be limited in accordance with the insulation strengths. The machine should be Y-connected, and it is highly desirable to ground the neutral solidly. Assuming 2 thicknesses of ground insulation on such a machine, a very effective method of protection is demonstrated in Figs. 9 and 10.

The protection of the turn insulation should be considered next. The winding using concentric turns, (one actually inside another within one slot) which was introduced in Europe for high voltage machines, should give adequate protection to the turn insulation if the ground insulation is protected properly. Because of economic considerations in the construction, assembly, and possible replacement of coils, it is unlikely that this type of winding will be favored in the United States. Therefore, the more usual rectangular coil sections will be considered. If a greater part of the energy of the incoming wave could be by-passed into the succeeding turns of the machine, adequate protection could be attained. However, there seems to be no way of accomplishing this without an undesirable complexity in the wiring connections. In previous articles^{5,8,9,13} it has been shown conclusively that sloping off the incoming wave will give adequate protection to the turn insulation. General recommendations have been made.^{8,13}

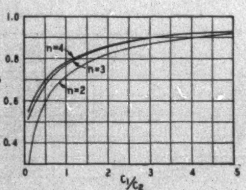


Fig. 11. Curves showing values of ξ_b in terms of C_1 and C_2 (see eqs 20 and 25)

However, for large and important machines, special consideration should be given each specific case to predetermine (1) the maximum allowable rate of rise of voltage at the machine terminals and (2) the size of the apparatus needed to limit the rate of rise to that maximum value. These 2 features are discussed in detail in Appendixes I and II, respectively, but will be described briefly now.

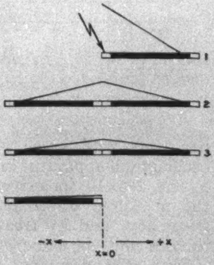
On the mulitum coil winding, the procedure outlined for determining the protection of the turn insulation is as follows: Make the calculations indicated by eq 25, with the aid of Fig. 11. Choose the appropriate factor of safety based upon the factory test voltage that has been used for the turn insulation. Determine the shortest allowable time in microseconds for the surge to reach crest value, on the assumption of a straight line voltage rise, and from this determine the maximum rate of rise of terminal voltage. Then the apparatus required to limit the rate of rise to this maximum value can be calculated according to Appendix II. If this is to be done according to the scheme in which the condenser is fed through 2,000 ft of line, the approximate surge impedance of the machine and of the overhead line must be known. Then, using the maximum rate of rise of terminal voltage just found and curves made up from eqs 35, 36, 37, and 38, the appropriate value of capacitance to be placed at the machine terminals can be established.

Appendix I—Calculation of Maximum Allowable Rate of Voltage Rise

It is desired now to develop some means of estimating the maximum voltage between turns of the first coil in a multiturn coil armature winding when a voltage having a given rate of rise is applied at the machine terminals. Tests show this maximum to occur during the first 1 or 2 μsec after the voltage is applied if the rate of rise at the terminals is steep. When the rate of rise at the machine terminals is not steep, the maximum voltage between turns may occur later, but does not seem to be of sufficient magnitude to warrant study at this time. In the former case, the maximum voltage between turns occurs when the wave has had about time to travel around one turn of the winding and come back under itself. This is based upon an assumed velocity of the main wave in the first turn equal to the average velocity of the main part of the wave in the entire machine. However, this maximum voltage between adjacent turns is considerably less than the voltage to ground on the terminal lead at this same instant. This shows an appreciable induced voltage in the other turns of the first coil while the main incoming wave is in the first turn of the first coil.

The turns may be represented as shown in Fig. 12, where the open conductors represent the end turns and the solid conductors the parts of the coils which are in the slots. The point at the right end of turn 1 in the Fig. 12 is identical with the left end of turn 2, etc. The problem is similar to that of several parallel lines. It will be shown that a satisfactory solution can be obtained for the voltage distribution in the first coil by treating the multiturn coil as *n* parallel no-loss lines of infinite length. They can be treated as being of infinite length because the waves have not come quite back to a point just above or below their starting points at the time of maximum voltage between the first 2 turns, and it is only up to this instant for which calculations need be made.

Fig. 12. Representation of turns in a multiturn coil armature winding



The problem of *n* parallel lines with one line discontinuous will be considered next. The surge will be assumed to originate at the point of discontinuity on line 1, at which point $x = 0$. The form of the general equations to be used at any given value of x is

$$
\begin{aligned}
V_1' &= K_{11}\, q_1' + K_{12}\, q_2' + \ldots + K_{1n}\, q_n' \\
V_2' &= K_{21}\, q_1' + K_{22}\, q_2' + \ldots + K_{2n}\, q_n' \\
\cdot\quad & \quad\cdot \qquad\quad \cdot \\
\cdot\quad & \quad\cdot \qquad\quad \cdot \\
\cdot\quad & \quad\cdot \qquad\quad \cdot \\
V_n' &= K_{n1}\, q_1' + K_{n2}\, q_2' + \ldots + K_{nn}\, q_n'
\end{aligned}
\qquad (1)
$$

where the V's designate voltage, the K's coefficients of potential, and the q's charges per unit length of conductor. The subscripts indicate the numbers of the lines, and the primes indicate relations existing to the right of the point where $x = 0$. Similar equations can be established to express the relations existing to the left of the point where $x = 0$; double primes will be used in those equations.

On any line m,

$$-\frac{\partial i_m'}{\partial x} = \frac{\partial q_m'}{\partial t}$$

where t indicates time in seconds. Similarly,

$$-\frac{\partial i_m''}{\partial x} = \frac{\partial q_m''}{\partial t}$$

This leads to a set of differential equations:

$$\left.\begin{aligned}
-\frac{\partial V_1'}{\partial t} &= K_{11}\frac{\partial i_1'}{\partial x} + K_{12}\frac{\partial i_2'}{\partial x} + \ldots + K_{1n}\frac{\partial i_n'}{\partial x}\\
-\frac{\partial V_2'}{\partial t} &= K_{21}\frac{\partial i_1'}{\partial x} + K_{22}\frac{\partial i_2'}{\partial x} + \ldots + K_{2n}\frac{\partial i_n'}{\partial x}\\
&\vdots\\
-\frac{\partial V_n'}{\partial t} &= K_{n1}\frac{\partial i_1'}{\partial x} + K_{n2}\frac{\partial i_2'}{\partial x} + \ldots + K_{nn}\frac{\partial i_n'}{\partial x}
\end{aligned}\right\} \quad (2)$$

where the i's designate currents. Also, a set of relations may be set up for the voltage gradients:

$$\left.\begin{aligned}
-\frac{\partial V_1'}{\partial x} &= L_1\frac{\partial i_1'}{\partial t} + M_{12}\frac{\partial i_2'}{\partial t} + \ldots + M_{1n}\frac{\partial i_n'}{\partial t}\\
-\frac{\partial V_2'}{\partial x} &= M_{21}\frac{\partial i_1'}{\partial t} + L_{22}\frac{\partial i_2'}{\partial t} + \ldots + M_{2n}\frac{\partial i_n'}{t}\\
&\vdots\\
-\frac{\partial V_n'}{\partial x} &= M_{n1}\frac{\partial i_1'}{\partial t} + M_{n2}\frac{\partial i_2'}{\partial t} + \ldots + L_{nn}\frac{\partial i_n'}{\partial t}
\end{aligned}\right\} \quad (3)$$

where the L's and M's designate self and mutual inductances, respectively.

Solutions for the voltages and currents from these equations will be of the form

$$\left.\begin{aligned}
V'_m &= A_m f(x + \nu t) + B_m g(x - \nu t)\\
i'_m &= D_m f(x + \nu t) + G_m g(x - \nu t)
\end{aligned}\right\} \quad (4)$$

where A_m, B_m, D_m, G_m, and ν are constants.

The boundary conditions to be satisfied are

$$\left.\begin{aligned}
&q_1' \neq 0, \quad q_1'' = 0 = i_1''\\
&\text{Also, when } m \neq 1\text{, then for } x = 0\\
&V'_m = V''_m \quad i_m' = i_m'' \quad i_m' = \nu q_m'\\
& \quad i_m'' = -\nu q_m'' \quad q_m'' = -q_m''
\end{aligned}\right\} \quad (5)$$

From eq 1 it may be noted that

$$\left.\begin{aligned}
V_2' &= K_{21} q_1' + K_{22} q_2' + \ldots + K_{2m} q_m' + \ldots + K_{2n} q_n'\\
V_2'' &= \phantom{K_{21} q_1' +{}} K_{22} q_2'' + \ldots + K_{2m} q_m'' + \ldots + K_{2n} q_n''\\
&\vdots\\
V_n' &= K_{n1} q_1' + K_{n2} q_2' + \ldots + K_{nm} q_m' + \ldots + K_{nn} q_n'\\
V_n'' &= \phantom{K_{n1} q_1'} + K_{n2} q_2'' + \ldots + K_{nm} q_m'' + \ldots + K_{nn} q_n''
\end{aligned}\right\} \quad (6)$$

It may be observed that the boundary conditions are satisfied if $q_m'' = -q_m'$ and $V_m'' = V_m'$ not only for $x = 0$, but also for all symmetrical values of x; it will be assumed now that this is true, and also that the final solutions for current and voltage must be unique. It remains to be shown that, on the basis of these assumptions, solutions can be found of the form shown in eq 4. All the constants in the final solution will be determined because the boundary conditions have been satisfied by the assumptions just made.

Equations 6 occur in pairs (except for $m = 1$); consequently, $(n - 1)$ simultaneous algebraic equations in the q's can be formed and all values of q_m' or q_m'' found in terms of q_1'. Thus,

$$q_2' = \rho_2 q_1', \quad q_m' = \rho_m q_1' \quad \text{etc.} \quad (7)$$

where

$$\rho m = \frac{\begin{vmatrix}
K_{22} \ldots K_2\,(m-1)\,\frac{K_{12}}{2}\,K_2\,(m+1) \ldots K_{2n}\\
K_{32} \ldots K_3\,(m-1)\,\frac{K_{13}}{2}\,K_3\,(m+1) \ldots K_{3n}\\
\vdots \qquad \vdots \qquad \vdots \qquad \vdots\\
K_{n2} \ldots K_n\,(m-1)\,\frac{K_{1n}}{2}\,K_n\,(m+1) \ldots K_{nn}
\end{vmatrix}}{\begin{vmatrix}
K_{22} & K_{23} \ldots K_{2n}\\
K_{32} & K_{33} \ldots K_{3n}\\
\vdots & \vdots \quad \vdots\\
K_{n2} & K_{n3} \ldots K_{nn}
\end{vmatrix}} \quad (8)$$

Then,

$$\left.\begin{aligned}
&V_1' = (K_{11} + \rho_2 K_{12} + \rho_3 K_{13} + \ldots + \rho_n K_{1n})q_1' = \sigma_1 q_1'\\
&\text{where}\\
&\sigma_1 = (K_{11} + \rho_2 K_{12} + \ldots + \rho_n K_{1n})
\end{aligned}\right\} \quad (9)$$

Thus,

$$-\frac{\partial V_1'}{\partial t} = \sigma_1 \frac{\partial i_1'}{\partial x} \quad (10)$$

Similarly, since $i_m = \nu q'_m$, then

$$\left.\begin{aligned}
&-\frac{\partial V_1'}{\partial x} = \lambda_1 \frac{\partial i_1'}{\partial t}\\
&\text{where}\\
&\lambda_1 = (L_1 + \rho_2 M_{12} + \ldots + \rho_n M_{1n})
\end{aligned}\right\} \quad (11)$$

Then,

$$\frac{\partial^2 V_1'}{\partial t^2} = \frac{\sigma_1}{\lambda_1}\,\frac{\partial^2 V_1'}{\partial x^2} \quad (12)$$

From which

$$V_1' = A_1 f(x + \nu t) + B_1 g(x - \nu t), \text{ where } \nu = \sqrt{\sigma_1/\lambda_1} \quad (13)$$

$$q_1' = \frac{V_1'}{\sigma_1}\text{; and } i_1' = \frac{\nu}{\sigma_1} V_1'; \quad V_m' = \frac{\sigma_m}{\sigma_1} V_1'; \; i_m' = \rho_m i_1' \quad (14)$$

From the foregoing, any value of current and voltage can be established, but the relations are still very clumsy for engineering use, because ρ_m, σ_m, etc., require too much time to calculate. The problem must be simplified further.

In doing this, first consider the case of n parallel lines all continuous with a surge originating on line 1 at a point $x = 0$. Then general relations and boundary conditions can be written in a manner similar to that just outlined. If it be assumed that all charges and currents are zero on lines other than that on which the surge originates, a solution may easily be found that fits all boundary conditions. The voltages on all lines are linked in a simple electrostatic field problem where charges exist only on line 1.

If the system with one line discontinuous can be expressed in terms of the case with all lines continuous and some capacitance coupling constants, the problem is simplified readily. (In passing, it may be mentioned that by superposing these 2 solutions, almost any desired boundary conditions can be satisfied.) The 2 cases that have been discussed are shown in Figs. 13B and 13A, respectively. It may be noticed that in Fig. 13B an additional line has been inserted to the left in the No. 1 position. If all lines could be assumed negligibly small, and the usual assumptions concerning circuit constants are considered, it is seen that the presence of line 1 to the left, when not electrically joined to anything at point $x = 0$, has no effect on the electrostatic field.

Now, if the surge in Fig. 13B were applied on the left-hand part of line 1 and this superposed on Fig. 13B, all charges on lines other than No. 1 would cancel, and all voltages on lines other than No. 1 would be doubled. The charge on all parts of line 1 would be the same, out as far as the waves had traveled from point $x = 0$. The voltage on lines 1, right or left, would be ${}_bV_1' + {}_bV_1''$.

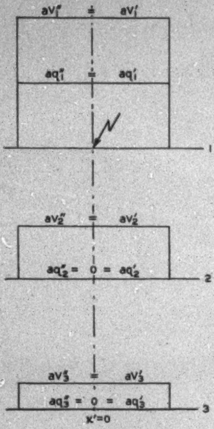


Fig. 13A

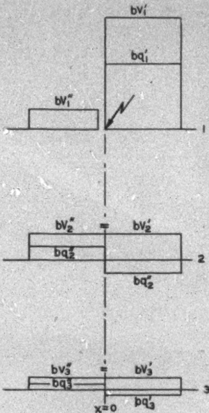


Fig. 13B

The problem now is to find the relation that will give ${}_bV_1'/{}_bV_2'$ in terms of ${}_aV_1'/{}_aV_2'$ and any simple arrangement of capacitances, because from the foregoing it is apparent that ${}_aV_1'/{}_aV_n'$ is much easier to establish than ${}_bV_1'/{}_bV_n'$ by straight arithmetical calculation. This relation can be established as follows:

$$\text{Let } {}_aV_1' = {}_bV_1' + {}_bV_1''; \text{ then } {}_aV_2' = 2{}_bV_2' \tag{15}$$

$$\text{Let } \xi_a = \frac{{}_aV_1' - {}_aV_2'}{{}_aV_1'} = 1 - \frac{2{}_bV_2'}{{}_bV_1' + {}_bV_1''} \tag{16}$$

$$\text{or } -\frac{{}_bV_1'}{{}_bV_2'} - \frac{{}_bV_1''}{{}_bV_2'} = \frac{2}{\xi_a - 1} \tag{17}$$

Now, ${}_bV_1''$ can be obtained in terms of ${}_bV_2'$ as follows: By Fig. 14A, C_1 and C_2 are defined, and it can be written that

$${}_bV_1'' = \frac{C_2}{C_1 + C_2}{}_bV_2''; \quad \text{then } {}_bV_2' = {}_bV_2'' \tag{18}$$

and

$$-\frac{{}_bV_1'}{{}_bV_2'} = \frac{2}{\xi_a - 1} + \frac{1}{C_1/C_2 + 1} \tag{19}$$

and

$$\xi_b = 1 - \frac{{}_bV_2'}{{}_bV_1'} = 1 - \cfrac{1}{\cfrac{2}{1 - \xi_a} - \cfrac{1}{\cfrac{C_1}{C_2} + 1}} \tag{20}$$

The value of ξ_a can be expressed readily in terms of C_1/C_2 and the number of lines, n, since it simply involves the relative voltages at points connected by the chain of capacitances as shown in Fig. 14A when a charge is placed only on the first conductor (at the top of the chain). This makes it possible to plot ξ_b as a function of C_1/C_2 for various numbers of conductors n. This will be made use of later.

Numerical calculations have shown that the capacitances between the end turns are not negligible quantities. The capacitance to ground in the end windings is relatively small and the inductance is small, so the end winding probably should be considered as joining the conductor of one slot to another by a small capacitance coupling, and as furnishing lumped capacitances of considerable size between adjacent turns within each coil side. However, even this sort of an approximation results in very involved calculations. Reasonable results can be obtained by assuming the capacitance between turns in the end windings to be distributed uniformly in the slots, and by assuming the end turns to perform the duty merely of conducting links between slot conductors.

A further approximation is involved in the treatment of the slot problem, which is as follows: In reality, the electric wave is retarded greatly so that it is no longer possible to assume that the electrostatic and electromagnetic fields lie in planes strictly perpendicular to the conductor. However, the insulation thickness relative to the length of the slot is very small, and the distortional effect on the wave in going around one turn, due to the reduced velocity and changed constants, is probably small. An idea of the accuracy of this method of calculation can be obtained from Fig. 15.

It is customary to test the turn insulation before coils are assembled in the machine, by impressing a voltage E_T at high frequency across each armature coil. The voltage per turn under this condition will be equated to that experienced on a surge with a given rate of rise at the machine terminals. Factors of safety can be taken on this at the discretion of the designer.

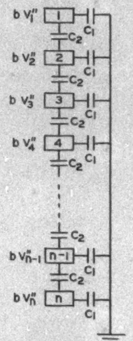


Fig. 14A

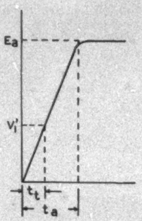


Fig. 14B

Refer to Fig. 16; then by the arrester setting,

$$E_a = \xi_0 \sqrt{2}\, E_g \tag{21}$$

where E_a = arrester voltage, E_g = line-to-ground voltage of the machine, and ξ_0 is a constant defined by eq 21. From Fig. 14B,

$$V_1' = \frac{t_t}{t_a}E_a, \text{ and } (\xi_b)V_1' = \frac{t_t}{t_a}\xi_b E_a \tag{22}$$

where t_t = time in seconds for the wave to travel around one turn; t_a = time in seconds for the wave to reach crest value E_a, on the assumption of a straight line rise in voltage. This will be equated to the crest voltage on the high frequency test as follows:

$$\frac{t_t}{t_a}\xi_b\,\xi_0 \sqrt{2}\,E_g = \frac{E_T}{n}\sqrt{2}, \text{ giving } t_a = n\,t_t\,\xi_b\,\xi_0\frac{E_g}{E_T} \tag{23}$$

where n = number of turns per coil. Assuming the wave velocity in the slot as 10,000 miles per second, and that in the end winding as 125,000 miles per second,[5]

$$t_t = \left[\frac{2 \times lc}{12 \times 5{,}280 \times 10{,}000} + \frac{(MT) - 2\,lc}{(12 \times 5{,}280 \times 125{,}000)}\right] \tag{24}$$

where lc = core length of machine and MT = coil mean turn length, both in inches. The ξ_b is calculated as shown in eq 20 and

$$t_a = n\,\xi_b\,\xi_0 \frac{E_g}{E_T}\frac{1}{63.36}\left[\frac{2\,lc}{10} + \frac{(MT) - 2\,lc}{125}\right]10^{-6} \tag{25}$$

(Note that ξ_b is plotted in curve form, as shown in Fig. 11.)

Appendix II—Calculation of Protective Apparatus Required

The rate of rise of the voltage at the machine terminal[illegible]y be limited by a capacitor at the terminals fed through a given length of line, as has been described in a previous article.[8] This scheme is indicated in Fig. 16. An analysis to show the approximate performance of this scheme now will be given.

The machine is to be treated as a line of surge impedance, Z_2, so far as reflections at its terminals are concerned. The incoming surge, E, from the open line will be assumed to have a steep front and long duration. The wave to the right of the arrester will have practically an infinitely steep front to arrester voltage and a flat top for several microseconds thereafter. If this wave suffered no reflections, it would remain flat topped until the voltage of the tail of the incoming wave, E, dropped below the arrester voltage, E_a. However, reflections do occur at the machine, and in turn produce other reflections at the arrester, which must be considered. This requires certain assumptions concerning the arrester performance, as follows:

1. If the arrester draws current, it will be such as to limit the arrester voltage to E_a.

2. If the arrester draws no current, the voltage, e_a, across the arrester is such that $-E_a < e_a < +E_a$.

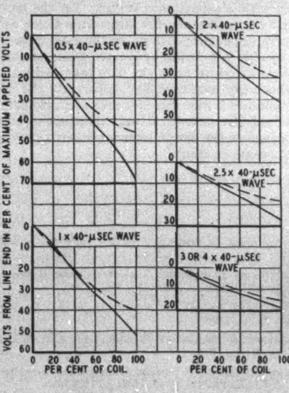


Fig. 15. Comparison between calculations and test results. Solid lines determined by tests; dotted lines by calculations

In fulfilling the first condition, voltage waves arriving at the arrester from the machine may be thought of as passing over the arrester and, simultaneously, voltage waves of equal form but opposite sign must be considered as emanating from the arrester and traveling in both directions from the arrester. The resulting current waves can be calculated readily. When condition 2 of the arrester performance is reached, it will become apparent in such a calculation. So far as conditions between the arrester and machine are concerned, and until the condition 2 for the arrester is reached, it is as though the voltage waves arriving from the machine to the arrester were completely reflected at the arrester with reversed signs. If the line surge is of a sustained large magnitude, arrester condition 1 exists long enough to permit several oscillations to occur between the machine and the arrester.

Consider then the first wave passing over the arrester. It is rectangular and flat topped; upon reaching the machine terminals, the following relations hold:

$$E_2 = E_c = E_a + E_{r0} = i_2 Z_2 \tag{26}$$

where E_a = voltage across the arrester; i_2 = current entering surge impedance Z_2; E_c = the voltage across the capacitor; E_2 = voltage on Z_2 at the capacitor and E_{r0} is the reflected wave defined by eq 26.

$$i_1 = \frac{E_a - E_{r0}}{Z_1} \text{ and } i_c = c\frac{dE_2}{dt} = i_1 - i_2 \tag{27}$$

$$C\frac{dE_c}{dt} = \frac{E_a}{Z_1} - \frac{E_c}{Z_1} - \frac{E_c}{Z_2} + \frac{E_a}{Z_1} \tag{28}$$

where C = capacitance of the capacitor and Z_1 = line surge impedance. Arranging in operational form,

$$\frac{E_c}{E_a} = \frac{2}{Z_1 C}\left(\frac{1}{\frac{Z_2 + Z_1}{Z_2 Z_1 C} + p}\right)1 \tag{29}$$

where p = the differential operator $\frac{d}{dt}$, and 1 represents Heaviside's unit function. Then,

$$\frac{E_c}{E_a} = S(1 - \epsilon^{-\alpha t_1}) \tag{30}$$

where

$$S = \frac{2Z_2}{Z_2 + Z_1}, \qquad \alpha = \frac{Z_2 + Z_1}{Z_2 Z_1\,C}, \qquad t_1 = t - T_1,$$

t = time in seconds after wave reaches arrester; and T_1 = time in seconds for wave to travel from arrester to machine. A part of this wave returns to the arrester, namely $[(S - 1) - S(\epsilon^{-\alpha t_1})]$ and reflects there with reverse sign. A part, $S(1 - \epsilon^{-\alpha t_1})$, enters the machine winding. The time required for the voltage wave to travel from the machine to the arrester and back, $2T_1$, is only about 4.07µsec. The time required for a wave to reach the machine neutral and return, $2T_2$, is usually much longer on a large machine. (On the 25,000 kva synchronous condenser for which tests are reported in this paper, $2T_2 \cong 38$µsec.) Consequently, several reflections between the arrester and machine may occur before any effect from the machine neutral takes place at the machine terminals.

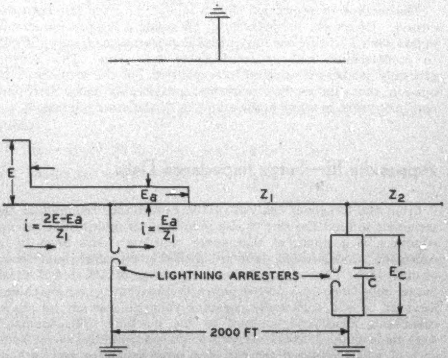


Fig. 16. Method of limiting rate of rise of voltage at machine terminals by a capacitor at the machine terminals fed through a given length of line

Hence, for $T_1 < t < 3T_1$, when $2T_2 > 2T_1$

$$\frac{E_c}{E_a} = S\,(1 - \epsilon^{-\alpha t_1}) \tag{31}$$

For $3T_1 < t < 5T_1$, when $2T_2 > 4T_1$, by the use of Heaviside's superposition theorem,

$$\frac{E_c}{E_a} = S(1 - \epsilon^{-\alpha t_1}) - (S - 1)S(1 - \epsilon^{-\alpha t_{11}})$$

$$+ \frac{d}{dt_{11}}\int^{t_{11}} S\,[1 - \epsilon^{-\alpha(t_{11} - \lambda)}] \cdot S \cdot \epsilon^{-\alpha\lambda} \cdot d\lambda \qquad (32)$$

or

$$\frac{E_c}{E_a} = S\,[1 - \epsilon^{-\alpha t_1}] - (S - 1)\,S\,[1 - \epsilon^{-\alpha t_{11}}] + \alpha\,S^2\,t_{11}\,\epsilon^{-\alpha t_{11}} \qquad (33)$$

where $t_{11} = t - 3T_1$

Similarly, E_c/E_a can be found for successive periods of time as $5T_1 < t < 7T_1$ when $2T_2 > 6T_1$, etc. These have been calculated for several periods, but require too much space to be included in this paper. Note, however, that when

$$\alpha t = 1; \quad Z_1 \geqq 250; \quad C \leqq 0.10 \times 10^{-6}; \quad 100 < Z_2 < 1{,}500 \qquad (34)$$

Then $t \geqq 7.14 \times 10^{-6}$, which is a far longer time than it takes for the wave to travel around one turn of any commercial machine; consequently, the values not of $\frac{E_c}{E_a}$ but of $\frac{d(E_c/E_a)}{dt}$, when the latter are largest are the things that are of greatest importance. These values of $\frac{d(E_c/E_a)}{dt}$ were determined from $\frac{E_c}{E_a}$ and are as follows:

$$\text{At } t = T_1; \ \frac{d(E_c/E_a)}{dt} = S\alpha \qquad (35)$$

$$\text{At } t = 3T_1; \ \frac{d(E_c/E_a)}{dt} = S\alpha[1 + \epsilon^{-2\alpha T_1}] \qquad (36)$$

$$\text{At } t = 5T_1; \ \frac{d(E_c/E_a)}{dt} = S\alpha[1 + (1 - 2\alpha ST_1)\,C^{-2\alpha T_1} + \epsilon^{-4\alpha T_1}] \qquad (37)$$

$$\text{At } t = 7T_1; \ \frac{d(E_c/E_a)}{dt} = S\alpha[1 + (2S^2\alpha^2T_1^2 - 4S\alpha T_1 + 1)\,\epsilon^{-2\alpha T_1} + (1 - 4\,S\alpha T_1)\,\epsilon^{-4\alpha T_1} + \epsilon^{-6\alpha T_1}] \qquad (38)$$

The method of protection shown in Fig. 17 often has been discussed. Of course, the problem of obtaining a lumped inductance makes such a scheme one for which the performance is very difficult to predetermine without considerable test data. This scheme generally has been considered too expensive, but the writer is of the opinion that the method warrants considerably more attention, and may prove in many applications to be the most suitable.

Appendix III—Surge Impedance Data

From the foregoing analysis of the capacitance required at the terminals to limit the rate of rise of voltage on multiturn armature windings, it is apparent that surge impedance data need to be collected. Considerable data are available on surge impedances of open lines. These usually lie in the range of 250 to 600 ohms. Surge impedance is a less definite physical entity for machines; however, it is a sufficiently constant value to warrant its use in calculating conditions external to the machine. Measurements were made on the 25,000-kva synchronous condenser by two methods, each of which required the use of a surge generator and cathode ray oscillograph:

1. A surge was applied to one end of one phase, and the rise in voltage at the open-circuited opposite end was recorded. The resistance to ground at the neutral required to reduce the maximum voltage at the neutral to half that found on open circuit was determined, and this was called one measure of the surge impedance.

2. The resistance equal to the surge impedance determined by the above method was left in at the neutral, and the voltage to ground and incoming current measured on surge at the machine terminal. The "surge impedance," then was determined as a function of time. Readings were taken for phase A with the rotor in and on the direct axis of phase A, and with the rotor in and on the quadrature axis of phase A (both with and without field excitation); readings also were taken with the rotor out. Waves of about 1 x 40 to 1 x 60 μsec and 10 x 40 to 10 x 60 μsec were used in each case.

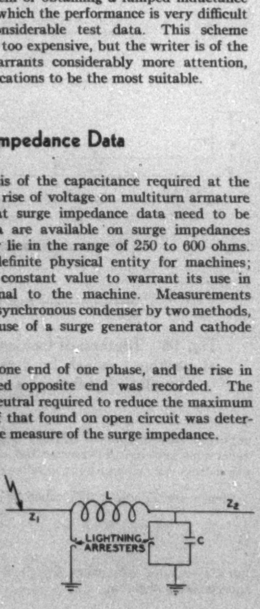


Fig. 17. Method of protection using lumped series inductance and shunt capacitance

These 2 test methods showed results as follows: (1) The average surge impedances measured by the different methods were of the same order of magnitude, though at some instants the second method might give values differing by 50 per cent from those determined by the first method; (2) there was no great effect of coupling between phases; (3) the surge impedance is about the same with the rotor in and on the direct axis as with the rotor in and on the quadrature axis, or with the rotor not in at all; (4) the change from 1- to 10-μsec fronts (with 40- and 60-μsec tails) on the applied surge had only a small affect on the average values of the surge impedance; (5) the values obtained on this 3-turn coil machine are much lower than those shown in certain earlier papers[5,13] on some other machines. The values obtained on the particular machine referred to in this paper were roughly as follows:

One section, phase A	365 ohms
Both sections, phase A, in parallel	190 ohms
All sections, all phases, in parallel	43 ohms

(Each phase had 2 parallels; in this tabulation, one section means one of these continuous circuits in one phase.)

The methods of measuring surge impedance by means of a surge generator and cathode ray oscillograph are somewhat cumbersome. It seems possible to obtain approximate data by the use of an oscillator and of a capacitance bridge. Suppose the machine reacts as a no-loss line. The impedance function (impedance *vs.* frequency) can be measured with an oscillator outfit. Its total capacitance to ground can be measured with a capacitance bridge. On the basis of these assumptions and measurements, the surge impedance can be determined. The surge impedance of both sections of phase A in parallel when found by this last method gave 145 ohms as compared with about 190 ohms found by using the data taken with the surge generator and cathode ray oscillograph. Apparently the use of the oscillator and capacitance bridge does not give accurate data, but when corrective methods are devised, it may be made to give a fairly good approximation of the surge impedance with only a small amount of work to obtain readings.

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Electric Power Switching

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A SYMPOSIUM on switching power at modern large generating plants is included on the program of the Institute's forthcoming winter convention. Five papers, each describing the facilities at one such plant, are to be discussed. Three of these papers are included in this issue, the other 2 having been included in the December 1933 issue. The following article serves as an introduction to this symposium.

AT ITS MEETING in Baltimore, Md., October 12, 1932, the Institute's committee on power generation decided to prepare this symposium because it felt that the profession wanted to know of the progress and improvement which had been made in switching large amounts of energy, the trends of the latest designs, and the limitations and operating experience which the recent types of stations had shown under actual working conditions. Accordingly a plan was developed for a group of papers not so much to bring out the description of a few typical modern large switching plants as to tell the reason for their existence and to explain their particular functional performance, how far the designs attained or fell short of the objectives which had been set for them, how adequately they met the requirements of present day operation, and what their records had been for serviceability and reliability. It was hoped also that trends or changes in the switchgear, and in bus and control arrangements would be indicated. Naturally, it was realized that the economic aspect of the designs was of great importance but because of the extra labor this would have required of the authors of the papers this phase of the investigation had to be foregone. The committee felt that if several authors would each prepare a paper on the modern plant with which he was thoroughly familiar, more of the worth while design, operating features, and intimate difficulties would be covered than by any other plan. With this material available then the engineering fraternity could make its own comparisons and draw its own conclusions.

The original plan contemplated 7 papers in all, 2 of them to be on the switching at hydroelectric plants, one from the West coast and one from the East coast. Unfortunately, it was not feasible to include these at the present time so the symposium consists of 5 papers on the switching of energy at steam-electric plants. A summary of these papers follows:

PERIOD

The switching plant designs treated in this symposium cover the period from 1922 to 1932 in the following order: Hudson Avenue 1922; Richmond 1925; Long Beach and State Line 1928, and Essex 1932. Thus there is a very uniform advance of time between the various plants described.

SIZE

All the stations are of large capacity, the individual ratings being as follows:

Hudson Avenue—planned for 400,000 kw; now 770,000 kw

Richmond—120,000 kw; in 1935, 285,000 kw

Long Beach No. 3—now 200,000 kw; ultimately 800,000 kw

State Line—350,000 kw;[1] ultimately 1,000,000 to 1,500,000 kw

Essex—330,000 kw[1] to 450,000 kw

VOLTAGES

A wide range of voltages for generation and transmission is represented in this group of stations, the particular values in each case being associated with the special functions of the individual plant.

Hudson Avenue—27.6-kv bus and feeders

Richmond—13.8-kv for feeders, frequency converter; 66-kv to transmit bulk power

Long Beach No. 3—16.5-kv paralleled on 220-kv bus, 66-kv substations

State Line—22-kv, 33-kv, 66-kv, and 132-kv feeders

Essex—24-kv bus and feeders

FUNCTION

These 5 stations represent the principal types of switching functions in most common use today on large systems. Each design, of course, has the fundamental problem of generator control, and in addition the various duties are as follows:

Hudson Avenue—system supply, frequency conversion, and interconnections

Richmond—feeders for system and railway supply, system ties, and interconnections with other systems

Long Beach—system supply and interconnections

State Line—wholesale supply and interconnection center

Essex—feeder supply to system substations and system ties

BUSSES

Many varieties of bus schemes are represented: the vertical isolated phase, the star design, a double bus sectionalized with reactors, the "*H*" connection,

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[1] Including units under construction.

Full text of a paper recommended for publication by the A.I.E.E. committee on power generation, and scheduled for discussion at the A.I.E.E. winter convention Jan. 23–26, 1934. Manuscript submitted Nov. 20, 1933; released for publication Nov. 20, 1933. *Not published in pamphlet form.*

2 duplicate rings, and the latest design, which presents a simple single bus with a single circuit breaker for each individual feeder.

Both indoor and outdoor busses are represented. In the former class 2 use air insulation, while 1 uses herkolite or micarta insulation on copper tubing. One outdoor installation uses rigid hollow copper conductors with solid insulation of micarta tubes in oil filled pipes or enclosures, and the other outdoor construction is at 220 kv, air insulated. Some of the designers indicate their approval of eliminating air as insulation for the busses yet find that other insulating materials present many problems. Furthermore, while some adopt oil as a bus insulating medium all are desirous of keeping to a minimum the amount of oil which might be released and ignited in case of a fault. It is in the estimation of the relative advantages and disdavantages of the various bus constructions that the widest divergence of opinion is expressed by the authors.

Protection and Service Record

All designs have the generator or unit step-up transformer neutral grounded, several of them using a reactor in the ground lead. The later plants have made full use of isolated metal housings, thus securing predetermined paths for the fault current and definite applications for the bus fault relaying. Practically all generators and autotransformers are relayed differentially as a unit.

Various relaying systems are used in the protection of the bus sections, synchronizing bus, feeders, etc., depending upon the type of bus scheme being used and the feeder service.

In spite of the differences in age and type of station design all plants have an excellent record for continuity of service and an exemplary standard of safety for the operating personnel. The authors' frank discussions of improvements required by some of the early apparatus and related developments in switching station design should be extremely helpful to engineers engaged in this field.

Trends

Higher voltages for bussing at the generating stations, and even for generators, are becoming more evident as is indicated by these plants.

There is a marked tendency toward the greater use of metal housings for circuit breakers and busses with ground fault protection, and an increasing interest in factory built complete units.

All the writers look forward to greater simplicity in switching layouts, improvement in design details, and perhaps a further approach to the unit principle.

Switching at State Line Station

A station having several unique features, including an outdoor oil-filled metal-clad 22-kv switchgear for main generator bus is referred to in this paper. The station forms an important link in a large and intricate transmission and distribution system. This paper is part of a symposium on electric power switching at modern large steam-electric generating plants.

By
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Chicago Dist. Elec.
Generating Corp.

ONE OF the more recent steam-electric power stations, involving some of the latest developments, is located about 14 miles from the business center of Chicago. It was built on "made" land on the shore of Lake Michigan, on the Indiana side of the Illinois-Indiana state line, hence its name, State Line station. It is the purpose of this paper to point out, following a brief picture of the station and its relation to the system, some of the problems and experiences peculiar to the electrical installation, particularly the switchgear.

The outstanding experiences at State Line with switching equipment have been incident to the use of a duplicate ring bus and outdoor oil-filled metal-clad switching equipment, using conventional oil circuit breakers. The duplicate ring bus has demonstrated its suitability for large generating units in giving an economical design, combined with great flexibility for handling unusual loading conditions. The performance of the metal-clad switching equipment has fully justified the expectation of its proponents in regard to safety and reliability and places it beyond the experimental stage. The next step, it is believed, should be the refinement of details and standardization of component parts.

Plant and System

The State Line station is owned and operated by the Chicago District Electric Generating Corporation (formerly the State Line Generating Company),

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Full text of a paper recommended for publication by the A.I.E.E. committee on power generation, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 31, 1933; released for publication Nov. 25, 1933. *Not published in pamphlet form.*

1. For all numbered references see list at end of paper.

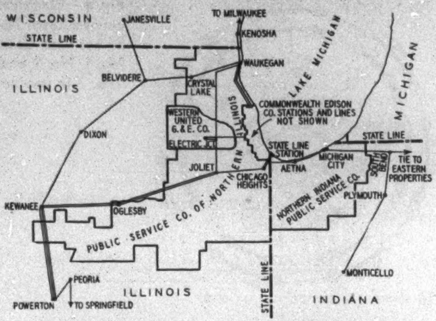

WISCONSIN
STATE LINE
JANESVILLE
TO MILWAUKEE
KENOSHA
WAUKEGAN
LAKE MICHIGAN
MICHIGAN
ILLINOIS
BELVIDERE
CRYSTAL LAKE
WESTERN UNITED G.&E. CO.
ELECTRIC JCT.
DIXON
COMMONWEALTH EDISON CO. STATIONS AND LINES NOT SHOWN
STATE LINE
STATE LINE STATION
MICHIGAN CITY
SOUTH BEND
TIE TO EASTERN PROPERTIES
JOLIET
NORTHERN ILLINOIS
AETNA
CHICAGO HEIGHTS
NORTHERN INDIANA PUBLIC SERVICE CO.
PLYMOUTH
KEWANEE
OGLESBY
PUBLIC SERVICE CO. OF NORTHERN ILLINOIS
MONTICELLO
PEORIA
ILLINOIS
INDIANA
STATE LINE
POWERTON
TO SPRINGFIELD

Fig. 1. Diagram of Chicago metropolitan district

which was organized to supply electrical energy on a wholesale basis to the public utilities operating in what is known as the Chicago metropolitan district.[1,2] This district may be considered roughly as the northeastern part of the State of Illinois and the northwestern part of the State of Indiana, an area of several thousand square miles, shown geographically in Fig. 1. The station serves not only as a generating plant for its customer companies, but also forms an important interconnection center for the district. The main interconnections of the system are shown in Fig. 2.

The station[4] at present has a generating capacity of 200,000-kw in a single 3-element unit, with a 150,000-kw unit under construction, and an installed feeder capacity of 520,000 kva. The system of which it forms a part has had a total peak load of approximately 1,250,000 kw, about 60 per cent of which was sold to large users, such as railways and industries. The system has at present an active generating capacity of approximately 1,700,000 kw, and has an interconnection with a group of properties to the east which has an additional capacity of approximately 2,500,000 kw. The station as originally planned was to have had an ultimate capacity of 1,000,000 kw in 5 units, but present indications are that the ultimate capacity will be about 1,500,000 kw.

The plant serves the system at present primarily as a modified base load station, normally carrying for 15 hours a day approximately full load, less a 10 per cent reserve, but varying its output over a range of about 8 per cent for regulation of the connecting tie line between the properties of the Chicago metropolitan district and the properties to the east. During the remaining 9 hours of the day, when the system has a light load, the plant output is varied over a wide range with the system load. The eastern properties regulate frequency and the companies in the Chicago metropolitan district regulate the flow of energy over the interconnection.

The station also performs an important secondary function made necessary by its position in the transmission network. It serves as an energy interchanging point, and incidentally controls as far as possible the flow of current into the various parts of the system.

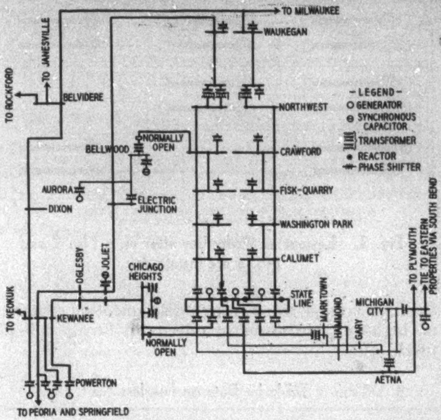

TO MILWAUKEE
WAUKEGAN
TO JANESVILLE
TO ROCKFORD
BELVIDERE
NORTHWEST
- LEGEND -
○ GENERATOR
⊖ SYNCHRONOUS CAPACITOR
TRANSFORMER
● REACTOR
PHASE SHIFTER
BELLWOOD
NORMALLY OPEN
CRAWFORD
AURORA
DIXON
ELECTRIC JUNCTION
FISK-QUARRY
WASHINGTON PARK
CALUMET
OGLESBY
JOLIET
CHICAGO HEIGHTS
TO KEOKUK
KEWANEE
STATE LINE
MARKTOWN
HAMMOND
GARY
MICHIGAN CITY
TO PLYMOUTH
TIE TO EASTERN PROPERTIES VIA SOUTH BEND
NORMALLY OPEN
AETNA
POWERTON
TO PEORIA AND SPRINGFIELD

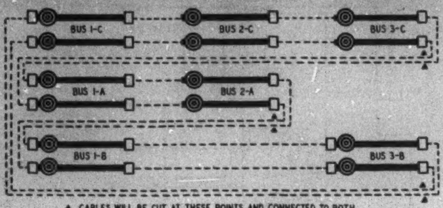
Fig. 2. Main connections of the Chicago metropolitan district's system

Two separate systems are used by the Commonwealth Edison Company for their main connections, and the supply from Powerton is brought into Chicago through 3 separate systems. For simplicity, generators and generator busses in the Commonwealth Edison Company and Public Service Company of Northern Illinois stations are not shown

The use of the plant for energy interchange, as well as generation, imposes unusual duties on the bus and switchgear and intensifies the problems of load concentrations and short circuits. It also made necessary the development of an extensive relay scheme to eliminate undue interruptions to service.

A concise description of the 22-kv generators and metal clad switchgear at State Line station has been given in a previous paper.[8] The initial main generating unit consists of 3 60-cycle 22-kv single-winding generators on 3 shafts driven by 1 high pressure and 2 low pressure elements of a triple cross-compound unit. The generator driven by the high pressure element is of 76,000-kw rating, while those driven by the low pressure elements are each 62,000 kw. In addition, each low pressure turbine drives a 4,000-kw 2,300-volt house generator. This unit can be operated if desired either with one low pressure element only, 2 low pressure elements only, or with the high pressure and one low pressure element only, thus giving necessary flexibility.

The voltage used for generation and distribution to the 10 main feeder transformer banks and the 2 station auxiliary transformers is 22 kv. Power is provided for station auxiliaries at 2,300 volts, and for small loads, at 440 volts. The transmission voltages and feeder transformer data are given in Table I. All feeder transformers are equipped for ratio adjusting and the 100,000-kva bank in addition is supplied with phase angle control[9] for load regulation. Both voltage and load regulation are accomplished by remote control and under load. The transformers connect directly to their lines on



▲ CABLES WILL BE CUT AT THESE POINTS AND CONNECTED TO BOTH ENDS OF FUTURE BUS SECTIONS TO BE INCLUDED IN RING

Fig. 3. Layout of 22-kv bus after units No. 2 and No. 3 are installed

the high voltage side through disconnecting switches, no high voltage busses or oil circuit breakers being used.

Table I—Data on Feeders

Three feeders of	20,000-kva capacity each at	33 kv[1]
Three feeders of	60,000-kva capacity each at	66 kv
One feeder of	60,000-kva capacity at	66 kv[2]
Two feeders of	60,000-kva capacity each at	132 kv
One feeder of	100,000-kva capacity at	66 kv[3]

All transformers are delta connected on the 22-kv side and Y-connected on the feeder side

1. Three-phase transformers; all others are banks of 3 single-phase transformers
2. Nitrogen filled type transformers; all others use conservators
3. Equipped with a separate phase shifter

22-KV BUS SCHEME

A sectionalized duplicate ring bus scheme was adopted as the most desirable for meeting all requirements.[5] Current limiting reactors shunted when desirable by remotely controlled oil circuit breakers, are inserted in each section between generators, and tie switches are provided between sections. In Fig. 3 is given an idea of the physical layout of the bus system, providing for the 3 generators of unit No. 1 and the double windings of units No. 2 and No. 3, and shows the method of expanding the bus as the station grows. In Fig. 4 is given diagrammatically an electrical conception of the ring bus showing the arrangement of the 7 generating elements comprising the first 3 units. A one line diagram of the main electrical connections in the first section is shown in Fig. 5.

Feeders to customer companies have been laid out in such a way that in the event of the loss of a generator or bus, the entire feed to any particular part of the system will not be lost, and also, so that feeders which normally carry incoming power are connected to different sections of the bus.

CONSTRUCTION AND ARRANGEMENT OF OUTDOOR METAL CLAD SWITCH GEAR

The main 22-kv switchgear, including the busses, connections, and breakers, is of a compact, outdoor, metal-clad oil-filled type.[6] A plan of the present switch yard is given in Fig. 6, showing all the equipment now installed and the locations of equipment to be installed when unit No. 2 is placed in service. The 3 rows of metal clad gear in the first section each consist of 7 bays forming a bus section structure.

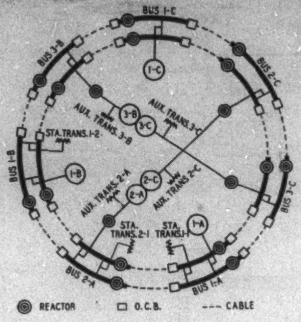


Fig. 4. Electrical conception of 22-kv bus with Units No. 1, No. 2, and No. 3 in service

The second section area of the yard contains 2 rows of gear, each containing 5 bays. There are also 2 isolated bays. Each bay accommodates 2 oil circuit breakers, 1 connecting to each of the 2 busses, "main" and "reserve."

The buses and switching equipment for 350,000 kw of generator capacity and 520,000 kva of feeder capacity, with one spare circuit, are accommodated in a switch yard of approximately 85,000 sq ft area. In this area are all the transformers and reactors with their spares, and all necessary track, with space reserved for future equipment.

In Figs. 7 and 8 are shown typical elevations of one bay each of the first and second section switchgear. A photograph of the first section part of the switch yard is reproduced in Fig. 9.

The oil circuit breakers are of the 3-tank type, arranged for disconnection from the bus by lowering. The 22-kv connections are made to the metal clad bus by means of male and female type contacts with spring retained fingers. The control connections are made in a similar manner. Current ratings are either 2,000 or 3,000 amp, depending upon the service. The interrupting capacity is 2,000,000 kva for breakers in the first section of the station, and 2,500,000 kva for those in the second section. These were the largest interrupting capacities available at the time of manufacture. Breakers in the same section are all interchangeable. All control voltages are 250 volts direct current supplied from a 760 amp-hr storage battery floating on a motor-generator set.

Potential transformers are open delta connected, the 2 transformers being enclosed in a single oil filled tank but separated by steel barriers. Fuses and current limiting resistors are provided in the tanks, and fuses may be removed or replaced while in service, without lowering the potential transformers.

Both the oil circuit breakers and the potential transformers are handled by means of motor operated elevators which roll on transfer trucks. The elevators may be run under any structure, and any breaker or potential transformer raised into the connected position, lowered to the disconnected position for protection or repairs, or removed to any other location. Hooks are provided in the structure whereby a breaker may be left in the disconnected position. While in this position, the tanks may be lowered on the elevators for internal inspection, and

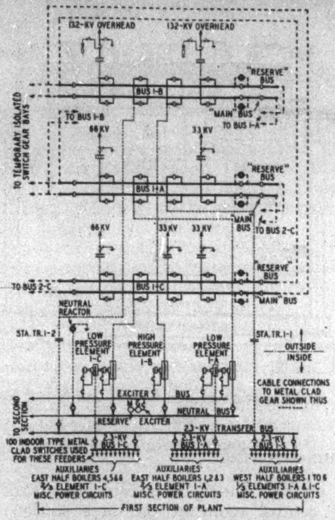

132-KV OVERHEAD
132-KV OVERHEAD
"RESERVE" BUS
BUS 1-B
"MAIN" BUS
TO BUS 1-A
TO BUS 1-B
66 KV
33 KV
TO TEMPORARY ISOLATED SWITCH GEAR BAYS
"RESERVE" BUS
BUS 1-A
MAIN BUS
TO BUS 2-C
66 KV
33 KV
33 KV
"RESERVE" BUS
TO BUS 2-C
BUS 1-C
"MAIN" BUS
NEUTRAL REACTOR
STA. TR. 1-2
LOW PRESSURE ELEMENT 1-C
HIGH PRESSURE ELEMENT 1-B
LOW PRESSURE ELEMENT 1-A
STA. TR. 1-1
OUTSIDE
INSIDE
CABLE CONNECTIONS TO METAL CLAD GEAR SHOWN THUS
TO SECOND SECTION
EXCITER BUS
M.G.S.
NEUTRAL BUS
RESERVE EXCITER
2.3-KV TRANSFER BUS
100 INDOOR TYPE METAL CLAD SWITCHES USED FOR THESE FEEDERS
2.3-KV BUS 1-C
2.3-KV BUS 1-A
2.3-KV BUS 1-S
AUXILIARIES
EAST HALF BOILERS 4,5&6
2/3 ELEMENT 1-C
MISC. POWER CIRCUITS
AUXILIARIES
EAST HALF BOILERS 1,2&3
2/3 ELEMENT 1-A
MISC. POWER CIRCUITS
AUXILIARIES
WEST HALF BOILERS 1 TO 6
1/3 ELEMENTS 1-A & 1-C
MISC. POWER CIRCUITS
FIRST SECTION OF PLANT

Fig. 5. One-line diagram of main electrical connections in first section

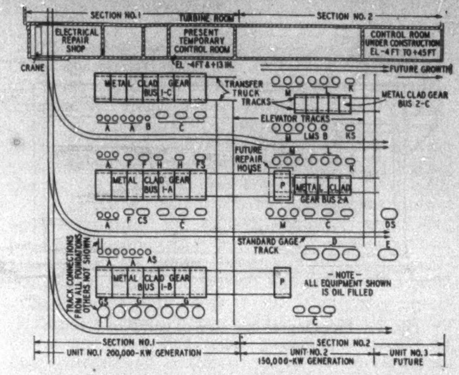

SECTION NO. 1
TURBINE ROOM
SECTION NO. 2
ELECTRICAL REPAIR SHOP
PRESENT TEMPORARY CONTROL ROOM
CONTROL ROOM UNDER CONSTRUCTION EL -4 FT TO +45 FT
CRANE
EL -4 FT & +13 IN.
FUTURE GROWTH
METAL CLAD GEAR BUS 1-C
TRANSFER TRUCK TRACKS
M
K
METAL CLAD GEAR BUS 2-C
A
A
B
C
ELEVATOR TRACKS
M
LMS
B
KS
FUTURE REPAIR HOUSE
A
F
F
H
H
FS
M
L
K
METAL CLAD GEAR BUS 1-A
P
METAL CLAD GEAR BUS 2-A
A
F
CS
C
M
C
DS
TRACK CONNECTIONS FROM ALL FOUNDATIONS OTHERS NOT SHOWN
STANDARD GAGE TRACK
D
E
A
A
AS
METAL CLAD GEAR BUS 1-B
P
- NOTE - ALL EQUIPMENT SHOWN IS OIL FILLED
GS
G
G
C
SECTION NO. 1
SECTION NO. 2
UNIT NO. 1 200,000-KW GENERATION
UNIT NO. 2 150,000-KW GENERATION
UNIT NO. 3 FUTURE

Fig. 6. Plan of switch yard for units No. 1 and No. 2

LEGEND

A.	Bus reactors
AS.	Spare bus reactor
B.	Neutral reactor
C.	66-kv transformer bank, 60,000 kva
CS.	Spare 66-kv transformer
D.	66-kv transformer bank, 100,000 kva
DS.	Spare 66-kv transformer
E.	66-kv phase shifter, 100,000 kva
F.	33-kv transformer bank
FS.	Spare 33-kv transformer
G.	132-kv transformer bank
GS.	Spare 132-kv transformer
H.	Station auxiliary transformer
K.	Unit auxiliary transformer
KS.	Spare unit auxiliary transformer
L.	Generator reactors
M.	Bus reactors
LMS.	Spare reactor
P.	Temporary isolated switchgear bay

practically all maintenance may be done without removing the breaker from its bay. Mechanical and electrical safety interlocks are provided, which prevent the lowering of tanks while the breaker is in the connected position, the raising or lowering of a breaker into or from the connected position while closed, or the closing of a breaker except while in the completely connected or disconnected position. Automatically operated shutters are provided which close off the bushings on the bus when a breaker is disconnected, thus providing safety against accidental contact, and reducing to a minimum the entrance of dirt.

While the second section switchgear is similar in fundamental construction to that of the first section, it is of later design. Rigid hollow copper conductors with solid insulation consisting of micarta tubes are used in the later design in place of insulated flexible cable,[5] and occasional micarta spacers are used instead of a varnished cambric spiral rope to maintain the bus concentrically within the enclosure. Modification of arrangements to facilitate shipment resulted in a higher but narrower and shorter structure. (Compare Figs. 7 and 8.)

Metal clad construction at this station is extended to the high voltage side of all outgoing feeder equipment except for the high voltage side of the 2 132-kv overhead lines. The transformer high voltage bushing is enclosed in an oil filled metal box bolted on to the transformer, and the outgoing cable enters this box through a pothead and connects to the center point of a double-throw externally-operated knife switch, permitting the cable to be either connected to the transformer, completely isolated, or connected to a test bushing mounted on the box. Observation windows and lighting arrangements are provided on the later transformers so that the position of the oil immersed switch blades may be observed directly. These switches are not designed to be operated with the line under load.

MAIN GENERATOR NEUTRAL EQUIPMENT

The neutral switching equipment is also metal clad, but of the indoor type, and is similar to the 2,300-volt auxiliary power equipment described below, but has a petrolatum compound around the bus. The generator neutral reactor of 8-ohms 1,588-amp capacity, is located outdoors in the switch yard.

SWITCH YARD POWER CABLES

Connections such as those between switch gear and transformers, and bus ties between bus sections, are made by means of lead covered cables. This, in addition to the outgoing feeders, results in a concentration of power cables which introduced problems from the standpoint of adequate heat dissipa-

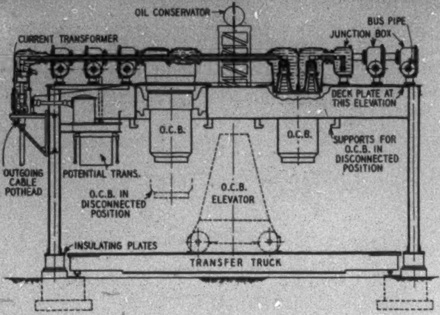

OIL CONSERVATOR
CURRENT TRANSFORMER
BUS PIPE
JUNCTION BOX
DECK PLATE AT THIS ELEVATION
O.C.B.
O.C.B.
SUPPORTS FOR O.C.B. IN DISCONNECTED POSITION
OUTGOING CABLE POTHEAD
POTENTIAL TRANS.
O.C.B. IN DISCONNECTED POSITION
O.C.B. ELEVATOR
INSULATING PLATES
TRANSFER TRUCK

Fig. 7. Elevation of one bay of unit No. 1 switchgear

tion. In this case, however, it was possible to install the cables under the water table.

Relay Protection

The relay protective scheme for the bus has been planned to combine a high degree of selectivity with completeness, every portion of the bus having automatic protection. In some cases this has resulted in an overlapping of protection, but a fault anywhere in the bus or its connections will not result in the loss of more than one generator or of enough feeder capacity to affect any one part of the system seriously.

Protection of the switchgear and bus including its reactors and tie cables is by means of a coördinated arrangement of ground fault relays, reactor differential relays, and bus tie cable differential relays, selectivity being obtained without time delay.

Generators of unit No. 1 are protected by means of conventional differential relays, opening armature, neutral, and field breakers, and shutting down generator ventilating fans. Unit No. 2 generator will be protected by a modified arrangement due to the use of a double winding in the generator and unit auxiliary transformers directly connected to the generator leads.

All transformers are protected by differential relays backed up by the line relays. On all circuits, except generators, overload relays are used, and on transformer banks operated with neutral grounded at the station, ground relays are also provided. On some circuits directional impedance relays are used in order to afford proper selectivity with the rest of the system. On the circuits feeding into Chicago (a distance of about 2 miles) pilot wire relays are used. The lack of switching on the high voltage side presents a problem in obtaining complete transformer protection, as complete clearing of the transformers in case of failure depends upon relays at the far end of the line, except on lines on which pilot wire relays are used. It is felt, however, that the cost of oil circuit breakers on the high voltage side cannot be justified, and no serious need for them has developed at State Line up to the present time.

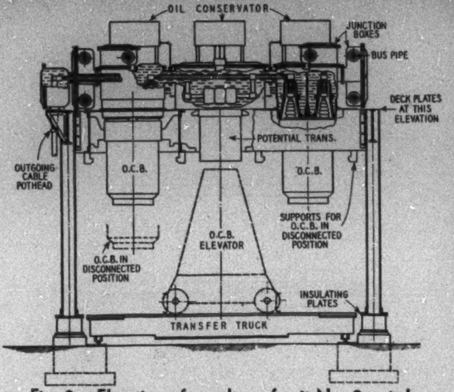

OIL CONSERVATOR
JUNCTION BOXES
BUS PIPE
DECK PLATES AT THIS ELEVATION
POTENTIAL TRANS.
OUTGOING CABLE POTHEAD
O.C.B.
O.C.B.
SUPPORTS FOR O.C.B. IN DISCONNECTED POSITION
O.C.B. ELEVATOR
O.C.B. IN DISCONNECTED POSITION
INSULATING PLATES
TRANSFER TRUCK

Fig. 8. Elevation of one bay of unit No. 2 switchgear

Switching Control

The present switchgear is controlled from a temporary control room in the first section of the building. The control equipment and instruments are mounted on steel switchboards.

The permanent control center is being constructed in the far end of the second section of the building adjacent to the switch yard, and it will be extended into the third section to take care of the ultimate plant. It has 3 main floors, a terminal room floor, a main control room, and a balcony.

The main control room will have a flat top benchboard in the center, upon which all of the control switches will be mounted. Vertical panels on one side of the room will have mounted upon them the instruments and gauges for the generators and important station equipment. On the other side of the room a similar vertical board will be used for feeder instruments. Likewise, on the balcony over the main control room, vertical panels will contain relays and miscellaneous meters for the generators and feeders. The boards for the new control center will be of ebony asbestos, and will be completely wired in the factory.

A chief operator located at a desk on the balcony will be able to supervise all control room activities, coördinating these with the boiler room and turbine room operations, and the requirements of the interconnected companies. Directly below the main control room is located the terminal room where all control and instrument wires will pass through terminal boards.

Some of the features being incorporated in the permanent control room are: The use of antivibration floors upon which are mounted the instrument and control panels, double windows in the turbine room wall, artificial ventilating system, and indirect lighting.

The cables used throughout the station for control and instrument circuits are all lead and armor covered, and are carried in groups through trenches, 8-in. metal ducts, and on metal shelving.

AUXILIARY SWITCHING

The 2,300-volt auxiliary power switching equipment is also metal clad, and is compactly arranged in switch rooms centrally located. The switches are remotely controlled. Bare conductors in air filled enclosures are used, without phase isolation, the system operating with ungrounded neutral. Breakers are of the vertical lift type. Motors are of the line start type, eliminating all starting equipment. In the lower part of Fig. 5, the general layout of the 2,300-volt auxiliary bus is shown.

Continuity of service is obtained by distributing the feeds to essential auxiliaries between the 3 busses, supplied from separate sources, and also by employing automatic switching of any bus to a standby transformer should a bus voltage fail. All of the essential auxiliaries consist of 2 or more units, so that a shutdown of any one auxiliary motor will not necessarily shut down a boiler or generating unit. Sections of the bus are located in separate rooms. Bus ground detectors are provided but no automatic protection is employed for the busses.

FIRE HAZARDS AND PROTECTIVE FEATURES

The concentration of equipment and the large amounts of oil present have made the question of fire hazard a very important one. Several effective precautions have been taken to avoid or minimize the effects of fire. The use of instantaneous type relays, comparatively high speed switching, and the limitation of ground fault currents, tend to reduce the chance of fire starting. Portable fire extinguishing equipment suitable for oil fires, and for use on live electrical equipment is provided at convenient locations to take care of small fires, and this is supplemented by foam generators and a large and reliable water supply system with conveniently located hydrants and hose equipment. The entire switch yard is covered with approximately 18 in. of coarse gravel, which has been proved by extensive tests to be effective in rapidly draining away oil and rendering it harmless as a fire hazard.

Ramps and curbs also have been provided for the indoor low voltage switch rooms. An organized routine has been developed for fighting fires. So far there have been no oil or electrical fires at this station.

OPERATING EXPERIENCE

The 22-kv switchgear for the first section at State Line station was installed in 1928 by a local contractor, under the supervision of the operating company's construction department, and placed in service, a few bays at a time, between November 1928 and April 1929. One-half of the second section switchgear was placed in service in June 1933. Construction on the remainder has not yet been completed.

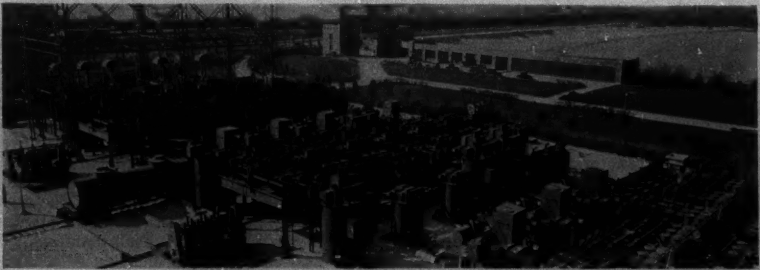
The electrical installation throughout the station is characterized by almost complete metal-clad construction, and this is undoubtedly responsible to a great extent for the high degree of safety and reliability with which the station has operated to date.

In common with most of the later plants, practically all of the station auxiliaries are electrically driven and controlled, which makes it necessary for large numbers of nonelectrical, as well as electrical, men to work close to complicated electrical equipment operating at voltages ordinarily considered hazardous. This situation, in addition to the regular higher voltage hazards, has made it necessary to give safety to personnel considerable thought, and it has been possible to operate and maintain the station to date without major or minor electrical accidents.

The reliability of the metal clad bus has been exceptionally good; no outages due to insulation failure or flashover have occurred. Breaker mechanisms and control wiring in the switch yard have caused some difficulties without, however, resulting in interruptions to service. In one case, however, a transformer was damaged due to an oil circuit breaker failing to open automatically with a short circuit on the line. This occurred during the first few months of service, and before the breaker mechanism remodeling had been completed by the manufacturer. The difficulties have been due almost entirely to outdoor exposure, and the problems of moisture and atmospheric impurities affecting control wiring, terminal blocks, and moving metal parts of breaker mechanisms were quite serious in the early period of operation, but have been practically solved by minor changes in design by the use of more suitable materials where necessary and more adequate protection of vital equipment from the elements. In some cases, where convenient, heaters have been installed to guard more completely against the effects of moisture condensation.

Immediately after installation, oil leaks developed

Fig. 9. First section part of switch yard



In the lower left-hand corner can be seen 1 of the oil storage tank cars, 2 of the movable elevators supporting 2 oil circuit breakers, and elevator crossover tracks used for rolling elevators to other structures or on to car for moving into repair shop

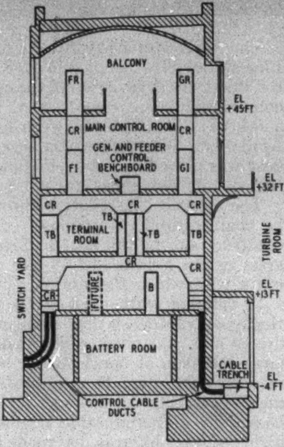


Fig. 10. Cross section of permanent electrical control center

LEGEND
FR. Feeder relays and miscellaneous meters
GR. Generator and station relays and miscellaneous meters
FI. Principal feeder indicating instruments
GI. Principal generator and station indicating instruments
CR. Cable racks, metal enclosed
TB. Terminal boards
B. Battery and d-c control panels

in many places due to porous metal castings; these were corrected by piening over the metal and subsequently on later equipment, by the use of a heavy oil-resisting varnish on the inside of the castings. Other oil leaks developed at the gasketed joints from time to time, especially with seasonal changes in temperature, causing expansion and contraction of the bus structure; such leaks have been effectively corrected to date by occasionally tightening up on the bolts. Tests are being conducted at the station, to determine whether there are more suitable or more easily applied materials than cork or vellumoid for this purpose. In a few cases it has been necessary to replace parts to correct leaks, but in no case has there been any serious leaks.

While no trouble has yet been encountered with either oil circuit breaker or potential transformer bushing flashovers in service, static discharges have been noted on bushings during periods of heavy fog when the bushings were not absolutely clean. Therefore, a program of thorough periodic cleaning and inspection of both male and female bushings during the late fall and early spring has been followed. During the summer overhauling of the breakers, bushings are again cleaned and also tested. These inspections have uncovered a few cases of small cracks and compound leaks.

Recently the use of the power-factor method of testing the male bushings and other breaker insulation to detect hidden weaknesses has been used with encouraging results, and it is thought that by combining this method with other means, it may be possible to eliminate completely all bushings having slight defects before trouble develops.

The performance of the oil circuit breakers has been very satisfactory, and under no condition has any breaker shown signs of distress after opening a fault current.

All breakers, mechanisms, and wiring of the outdoor gear are thoroughly overhauled once each summer and this has been found to be sufficient, except for occasional inspections after breakers have opened fault currents, at which time any necessary contact work or filtering is done.

A maintenance program, such as outlined above, can be efficiently followed at this station, as it is possible to do all necessary outdoor work during favorable weather conditions and use the maintenance men, who normally do switch yard work, on indoor work during adverse weather conditions. As the station grows, this may be difficult because of the increased amount of switch yard work, and it may be desirable at some future time partly to enclose, with thin removable siding, the sides of the oil circuit breaker structure below the deck plate. This arrangement might also be desirable in cases where traveling oil switch crews, which cannot be employed efficiently during inclement weather on inside work, are used for oil circuit breaker overhauling.

Other work which must be scheduled for the same months devoted to switchgear overhauling includes, in addition to the usual testing, filtering, and adjustment of oil levels in outdoor equipment, the overhauling of transformer tap changer mechanisms and contacts.

Due to close clearances and relatively small oil volumes, with a large number of points where moisture in the oil may collect, the moisture content of the oil has been closely watched on the first section equipment. It has been found that what little moisture has collected at the regular sampling points has been readily removed at the time the sample was taken, but some difficulty has been experienced in removing moisture from the long bus enclosures where the bus is supported by spiral varnished-cambric rope. This has been overcome in later designs by using, for bus supports, discs with slots in the periphery to permit free horizontal movement of oil and escape of air.

The method of handling oil may be of interest; a central oil storage system with permanent piping and pumps is not used, all equipment being portable. Three oil tank cars equipped with steam heating coils, 2 of which have a single 10,000-gal compartment and one having 2 5,000-gal compartments, are used both as storage tanks for spare oil and as a temporary means of handling oil during repairs and inspection of equipment. Filter presses and a centrifuge equipment with necessary pumps and numerous lengths of flexible metal hose equipped with fittings and valves are carried in an enclosed car.

Certain oil levels throughout the switch yard and all pressures on cable end bells are closely watched and recorded by the operators. The pressures have caused some difficulty because of considerable variation with load and outdoor temperature changes, and an attempt is now being made to reduce necessary pressure adjustment work by connecting several of the pressure reservoirs together into common headers. A few leaks which developed in the lead sheathing because of lamination of the lead were discovered before moisture was able to get into the cable by close watching of these pressures.

The use of 2 ring busses has resulted in sufficient flexibility to meet all maintenance requirements, as well as every condition of loading imposed on the station, both as a generating and distributing center. It was primarily the intention to use normally one bus at a time with the other held as a standby, but it has been necessary for the past 2 years to use both busses or portions of both busses to meet loading conditions.

A limited control over power distribution to the various lines is being accomplished by the use of 2 busses with proper switching of generators and feeders on to the busses with reference to the bus tie reactors, and this together with the use of the transformer ratio adjusters has provided control of the ampere loading of the different lines where necessary, due to maximum capacities being approached. The phase angle control provided on the 100,000-kva bank has been very effective in load division control.

In the event that some unusual load distribution causes overloading of a section of bus, the use of the corresponding section of the reserve bus in parallel is resorted to. Bus tie ammeters recently installed, assist the operator in analyzing, at a glance, loading conditions in the bus. Portable metering equipment consisting of an ammeter with a split core current transformer which may be slipped around any bus enclosure is also available if needed for detailed loading checks.

The question of voltage surges in the metal clad equipment has been given some study, and surges of values up to approximately 4 times the normal crest voltage to ground were recorded recently during a short test period. No troubles due to surges have been encountered.

Some fairly successful preliminary tests have been made to determine the feasibility of detecting, by means of a sensitive radio receiving set, discharges shielded by metal; should this method be developed to a reliable state, it would greatly assist in locating and correcting substandard equipment before a dangerous condition developed.

The possibility of trouble from poor contact in the disconnecting devices between breakers and structure has been watched for, but no serious trouble has so far developed at this station.

It has been pointed out that the use of metal clad gear makes for very safe normal operation, but it should also be noted that great care is necessary in opening up enclosures for inspection or repair, since it is impossible to test conductors at the point where an enclosing cover is to be removed. Extension contacts are provided which fit over the oil circuit breaker bushings while in the disconnecting position to make connections to the bus or to ground the bus if work is to be done.

Experience and tests point out the desirability of certain refinements in switch yards of the type used at State Line. The use of gravel covering the switch yard under and around the oil filled equipment as previously explained under "Fire Hazards" increases the difficulty of walking around the yard to make inspections or work on the equipment; concrete walks therefore should be provided, taking care that all such walks and also manhole covers which must be left exposed are given sufficient pitch to drain rapidly off into the gravel any burning oil which might run on to them. Plenty of permanently installed lighting equipment, as well as facilities for additional temporary lighting, also should be provided.

Due to the special design of this equipment, it has not yet been standardized to the point where it can be manufactured on a quantity basis and this means that in case of trouble which might possibly wreck a portion of the bus structure, considerable time would be required for replacement if it were necessary to await manufacture of new parts. In order to guard against such an interruption, considerable investment in spare parts for this gear has been necessary.

Spare transformers are not connected and no serious inconvenience has been encountered so far, although 2 transformer failures have occurred since the station was put in operation. When interchanging transformers, however, it is not necessary to remove potheads from the cables.

The use of a triple cross-compound unit, even though provision is made to operate the low pressure elements on boiler pressure steam by means of separate throttle valves and governors, would, in the event of a sudden loss of load or shutting down of the high pressure element, result in a momentary loss of load in the low pressure element generators, were it not for an automatic load relay which automatically admits high pressure steam to the low pressure elements, if the electrical output of the high pressure element falls below a predetermined value. Tests have shown that this device, assisted at the beginning by the stored steam, practically prevents loss of load in excess of that carried by the high pressure element.

There have been no instability difficulties to date between the plant and system. Governor action and voltage control have been satisfactory. Tirrill voltage regulators and a self-excitation system are now used, but pilot exciters will be used on units No. 2 and No. 3, and may be added later to unit No. 1.

TRENDS AND SUGGESTED IMPROVEMENTS

The popularity of compact outdoor oil-filled metal-clad switching equipment has steadily increased in the Chicago district, and much experience in the design and operation has been obtained.

The Public Service Company of Northern Illinois[3] has done considerable pioneering in the use of equipment of this type and is now employing it outdoors at 33 kv in 6 different locations, and at 132 kv at the Waukegan station.[7] The Northern Indiana Public Service Company is using this type of switchgear at 33 kv in its Marktown substation, and the Superpower Company of Illinois (Powerton station) is using it for the station 22-kv generator bus.

Recent developments of outdoor metal-clad gear have tended toward the use of more compact factory assembled units which may be shipped completely filled with oil. Manufacturers are now also offering gear with stationary breakers which use oil immersed knife switches or movable connectors for isolation of the breaker, instead of providing for isolation by vertical movement of the entire breaker. However, experience with the movable breaker scheme has been satisfactory at State Line and would seem to be simpler when disconnection is required only for work on the breaker. If, however, frequent disconnection is necessary to provide an additional visual break in a circuit for work beyond the breaker, facilities should be provided for doing this without the necessity of using a portable elevator.

It would be desirable in the case of an installation such as that at State Line, to provide individual motor-operated raising and lowering devices on at least the generator circuits, and this will possibly be done when the cost of such devices has been reduced to the point where they can be economically justified. This or some other means would also be desirable in the case of the 2,300-volt oil circuit breakers.

On outdoor switchgear, the deck plates under the busses (see Figs. 7 and 8) should be extended the full width of the structure, made absolutely water tight, and given a definite slope. This will prevent the formation of ice on the equipment under the deck plates and, in case of fire, drain any oil off into the gravel. If this were done and siding applied as previously mentioned, certain work which is now normally postponed during periods of bad weather, could be performed without inconvenience at any time.

The large number of gasketed joints used in oil-filled metal-clad gear and the inconvenience of replacement make it very desirable to simplify, as far as practical, such joints, and develop a gasket material of more lasting qualities and easy application than those available at present.

The use of silver-to-silver contacts for disconnecting switches and brazing or welding of all possible joints within the gear are desirable developments.

The use of indoor metal-clad gear, especially at voltages around 2,300 volts, is becoming well established, being used exclusively at the State Line, Powerton, and Michigan City plants. The Public Service Company of Northern Illinois is using considerable indoor metal-clad equipment, ranging up to 18 kv. The apparent trend in the case of indoor equipment, up to 15 kv, is to use tape or molded insulation with air, instead of oil or compound, resulting in simplicity and greater safety from fire. It should be noted that on indoor construction complete tightness of the enclosures is not usually provided, and there is some possibility of the entrance of foreign matter or hot gases and metallic vapors from a nearby fault. These are possibilities entirely avoided by the complete tightness of the oil-filled or compound-filled type of gear.

The thoughts on switchgear embodied in the foregoing, are largely the result of a close association with engineers connected with Sargent and Lundy, Inc., with the equipment manufacturers' engineers, and with associates in the construction and operating departments. The assistance of C. T. Hesselmeyer in the preparation of the paper and the helpful suggestions of other members of the electrical division are also acknowledged and greatly appreciated.

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Switching at Richmond Station

The essential features of the switching facilities at 13 kv and 66 kv at the Richmond generating station of the Philadelphia Electric Company are described in this paper. Operating experiences with such facilities are outlined and certain desirable improvements in future design are indicated. This paper is part of a symposium on electric power switching at modern large steam-electric plants.

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RICHMOND station of the Philadelphia Electric Company was placed in service in 1925, and is located in the city of Philadelphia, Pa. Switching at Richmond station is at 13.8 kv and 66 kv; a switch house structure of the vertical phase isolated design is used for 13.8 kv, and an outdoor

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Full text of a paper recommended for publication by the A.I.E.E. committee on power generation, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 25, 1933; released for publication Nov. 27, 1933. *Not published in pamphlet form.*

[1] For a more complete description of Richmond station itself than is given in this paper see the *Electrical World* for May 1, 1926, p. 907–26.

substation of the flat type with the bus insulators supported on steel pedestals is used for 66 kv.

The operating experiences outlined in this paper indicate that, since completion of certain modifications to the circuit breakers, the last of which were made about 2 years ago, switching facilities at Richmond Station which are adequate, reliable, easy to operate, and safe, have been obtained. The use of the straight double bus scheme is believed to contribute much to these results. It is questioned, however, whether the present type of isolated phase construction is the most desirable for 13.8-kv switching. It is also suggested that in the future circuit breakers may be applied which have lower interrupting ratings relative to the circuit breaker duties than generally used today. Features to be considered in future oil circuit breaker development also are discussed.

GENERAL

Richmond station[1] has sufficient land for considerable expansion and will very likely develop into a station of quite large capacity. Generation in the station is at 13.8 kv with transmission at this voltage to distribution substations and large industrial customers, and with transformation to 66 kv for transmission of bulk power to other parts of the system.

While Richmond station is not designed primarily as a base load plant, the economy of this station is such that it is operated at a very high load factor. With contemplated increases in the capacity of this station, its economy relative to that of other stations of the system possibly will be such that it will continue to operate as a base load plant for many years.

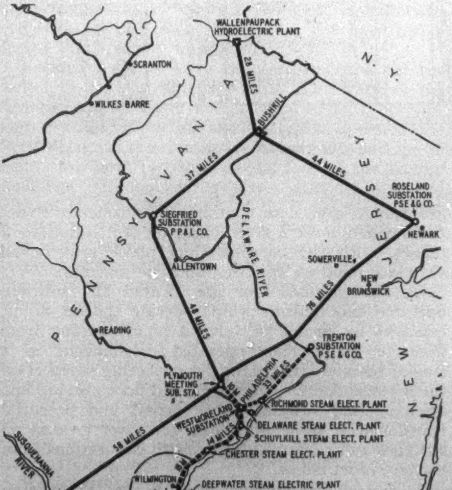
WALLENPAUPACK HYDROELECTRIC PLANT
SCRANTON
WILKES BARRE
N. Y.
28 MILES
BUSHKILL
37 MILES
44 MILES
ROSELAND SUBSTATION PSE & G CO.
NEWARK
PENNSYLVANIA
NEW JERSEY
SIEGFRIED SUBSTATION P P & L CO.
ALLENTOWN
DELAWARE RIVER
SOMERVILLE
NEW BRUNSWICK
48 MILES
78 MILES
READING
TRENTON SUBSTATION PSE & G CO.
PLYMOUTH MEETING SUB. STA.
10 M
PHILADELPHIA
33 MILES
RICHMOND STEAM ELECT. PLANT
WESTMORELAND SUBSTATION
DELAWARE STEAM ELECT. PLANT
SCHUYLKILL STEAM ELECT. PLANT
14 MILES
CHESTER STEAM ELECT. PLANT
58 MILES
SUSQUEHANNA RIVER
WILMINGTON
8 M
DEEPWATER STEAM ELECTRIC PLANT
DEL.
MD.
CONOWINGO HYDROELECTRIC PLANT
220 KV
66 KV OR LOWER

Fig. 1. Map of the system to which the Richmond generating station is connected

The present capacity of Richmond station is 120,000 kw in 2 generating units, comprising the initial installation; one of these units was placed in service in November 1925, and the other in January 1926. In addition to the 2 60,000-kw generators now in operation, a 165,000-kw generator is being installed which it is expected will be placed in service in 1935. The present total generating capacity of the Philadelphia Electric Company's system is about 900,000 kw.

Interconnections exist between the system of the Philadelphia Electric Company and the systems of the Pennsylvania Power & Light Company and Public Service Company of New Jersey; these interconnections at 220 kv constitute the so-called Pennsylvania-New Jersey interconnection. There is also an interconnection with the Public Service Company at 66 kv between Richmond station and Trenton, N. J. A moderate capacity interconnection exists with the Atlantic City (N. J.) Electric Company through the Deepwater generating station. There are also several light capacity interconnections with other companies in the surrounding territory. The relation of Richmond station to the rest of the system is shown by Fig. 1.

FEATURES OF ELECTRICAL INSTALLATION

The lines (all underground) in the Richmond station include 23 outgoing 6,000-kva 13.8-kv lines to distribution substations and substations in industrial plants, 2 43,000-kva 13.8-kv lines to the adjacent frequency converter substation for the supply of single-phase energy for railroad electrification, 3 12,000-kva 13.8-kv tie lines to Delaware generating station, and 2 60,000-kva lines to 13.8/66-kv bus tie transformer banks in the adjacent 66-kv substation. The 6,000-kva 13.8-kv lines are of no greater importance than those supplied from various other transmission centers on the system.

The ultimate capacity in generators, transformer banks, lines, etc., is not at all definite, and for this reason and the fact that such information is not essential in a review such as is given in this paper, figures on probable ultimate capacity are not given.

The 66-kv substation includes, in addition to the transformer banks, 4 lines which are part of the transmission system used for bulk power.

In Fig. 2 is given the essential electrical connec-

Table I—Oil Circuit Breaker Ratings and Duties

	O.C.B. Rated Current (Amp)	Maximum Load Current (Amp)	O.C.B. Interrupting Capacity (Kva)	Calculated Maximum Interrupting Duty (Kva)
13.8-Kv				
Generators				
60,000 kw	3,000	2,955	1,500,000	870,000
165,000 kw	5,000	4,630	1,500,000	1,160,000
Outgoing lines	600	263	780,000	280,000
Delaware tie lines	1,200	526	780,000	440,000
Frequency conv. substation lines	2,000	1,530	780,000	530,000
Bus tie trans. banks	3,000	2,510	1,500,000	1,250,000
66-Kv				
Transformer banks	800	557	1,500,000	800,000
Lines	800	440	1,500,000	800,000

tions of the generating station and of the step-up substation. It will be noted that the present 2 generators as well as the generator now being installed connect to the double 13.8-kv busses and that the 2 bus tie transformer banks provide connections between these busses and the double 66-kv busses. Some of the future generators will be connected through individual transformer banks directly to the higher voltage busses, depending upon system capacity requirements relative to the 13.8-kv distribution at Richmond.

The ratings of the old circuit breakers, both as to normal current capacity and interrupting rating in relation to the actual requirements, are given in Table I, the short-circuit duties being upon the basis of an assumed ultimate condition.

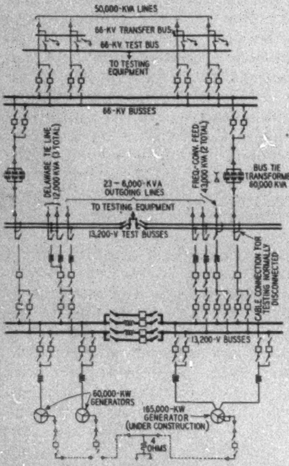
50,000-KVA LINES
66-KV TRANSFER BUS
66-KV TEST BUS
TO TESTING EQUIPMENT
66-KV BUSSES
DELAWARE TIE LINE 12,000 KVA (3 TOTAL)
FREQ.-CONV. FEED 43,000 KVA (2 TOTAL)
BUS TIE TRANSFORMER 60,000 KVA
23 – 6,000-KVA OUTGOING LINES
TO TESTING EQUIPMENT
13,200-V TEST BUSSES
CABLE CONNECTION FOR TESTING NORMALLY DISCONNECTED
13,200-V BUSSES
60,000-KW GENERATORS
165,000-KW GENERATOR (UNDER CONSTRUCTION)
4 OHMS

Fig. 2 (above). Single-line wiring diagram of Richmond station

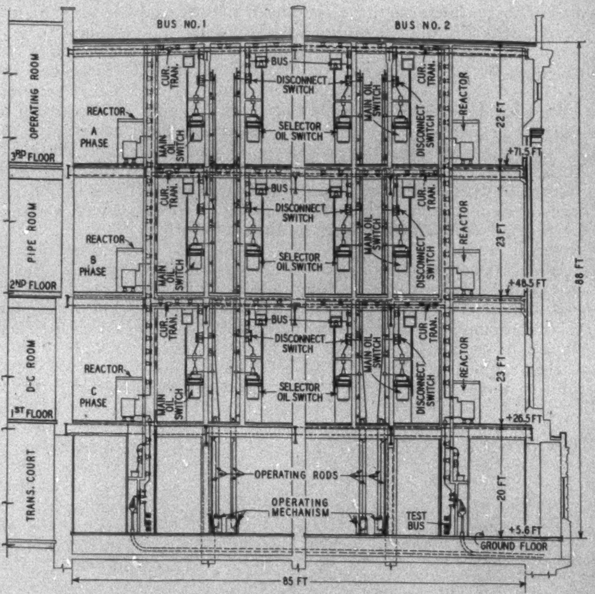
BUS NO. 1
BUS NO. 2
OPERATING ROOM
PIPE ROOM
D-C ROOM
TRANS. COURT
3RD FLOOR
2ND FLOOR
1ST FLOOR
REACTOR
A PHASE
B PHASE
C PHASE
CUR. TRAN.
MAIN OIL SWITCH
BUS
DISCONNECT SWITCH
SELECTOR OIL SWITCH
OPERATING RODS
OPERATING MECHANISM
TEST BUS
GROUND FLOOR
22 FT
23 FT
23 FT
20 FT
88 FT
+71.5 FT
+48.5 FT
+26.5 FT
+5.6 FT
85 FT

Fig. 3 (right). Cross section of Richmond switch house ("H"-pair line section)

It is the practice to provide a liberal amount of insulation on all switching facilities, particularly the bus and that portion of the connections which would not be isolated automatically in the event of failure. To this end the equipment in the 13.8-kv switch house has a nominal voltage rating of 25 kv. In the 66-kv outdoor substation the bus insulators and disconnecting switches are rated 110 kv, and the oil circuit breakers 73 kv.

The generator neutrals are grounded through a 4-ohm resistor so that with ground faults occurring in the switch house or on a cable the current is limited to a relatively low value. Thus the 13.8-kv circuit breaker duty is very moderate in the majority of operations.

It is expected that circuit breakers installed in the future on 13.8-kv outgoing lines, for which the calculated interrupting duty is 280,000 kva, will be considerably lower in interrupting rating than those now in use.

SWITCH HOUSE STRUCTURE

The 13.8-kv switch house structure, which is of the vertical phase isolated design, is shown in cross section in Fig. 3. The first, second, and third floors are similar, each floor containing the concrete structures which house a given phase for No. 1 and No. 2 busses, with the corresponding phase selector oil switches, main oil switches, and line reactors.

On the ground floor are located the solenoid operated mechanisms which operate the oil circuit breakers by means of vertical pipes running from floor to floor. Hand-operated mechanisms in a similar manner control the disconnecting switches on the 3 phase-floors. On the ground floor also are line disconnecting switches, line current and potential transformers, cable potheads, generator ground oil switches and cable test busses with connections from the test room below.

A central longitudinal wall divides the switch house so that on one side of the 3 phase-floors No. 1 bus with all of its breakers, disconnecting switches and reactors are separated from bus No. 2 on the other side with all of its corresponding equipment. A central corridor on each floor, at right angles to the above mentioned wall, divides the switch house into 2 parts, with approximately equal capacities and loads on each.

The 13.8-kv busses are sectionalized by means of reactors and the associated oil circuit breakers trip automatically in case of fault on a bus section. The 13.8-kv lines are arranged in pairs using the "H" connection with the main oil circuit breakers on each line automatically operated for faults, and with the selector breakers also provided with relays for tripping in case the main breaker does not function properly.

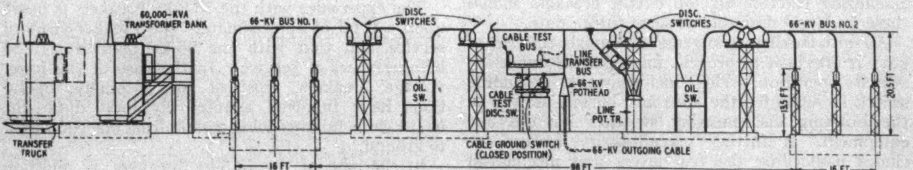

Fig. 4. Cross section of Richmond step-up substation

The electrical connections employed are such as to give operating simplicity while at the same time providing ample flexibility and reliability. The simple and symmetrical electrical connections permit of a simplified physical arrangement with a 7-ft wide section through the switch house for each generator, and a 5-ft section for each transformer bank, frequency converter feeder, and line pair. This scheme of connections also makes possible an arrangement of control switches, instruments, etc., that is not likely to confuse the operator, a factor which is very important.

Various features have been incorporated in the switch house design to minimize the extent of the trouble which might result from a fault current. Barriers have been installed between floors in the vertical copper runs on the various circuits and smoke caps have been provided at the tops of the barrier bushings. Smoke barrier plates also are provided around the operating rods of the breakers and disconnecting switches where they pass through openings in the floor. In the case of the potential transformers where taps are involved from 2 phase-floors, smoke barriers are applied to the bushings where they pass through the compartment side walls. Additional features include the fireproofing of generator neutral cable in all places where it runs exposed through the basement, the installation of barriers in the basement ceiling where connections are carried through from the test set to the test bus, and also barriers in the ceiling of the oil filter room in the openings through which the test set leads are carried up into the test bus compartments.

While the principal reliance against errors in switching or blocking is placed on the selection and training of the operating personnel, rather extensive use has been made of interlocking facilities to guard against errors which might result in personal injury, interruption to service, or damage to equipment. In the switch house, mechanical interlocks are provided to insure correct operation of disconnecting switches in relation to their associated oil circuit breakers. Compartment doors must be unlocked with a key released only when the proper disconnecting switches are open. Bus section grounding switches cannot be closed until a test has been made to insure that the bus is deënergized.

All generator and line sections in the switch house are plainly designated on the compartment doors and by suitable targets on exposed equipment such as the operating mechanisms of the oil circuit breakers and disconnecting switches.

Certain control interlocks are provided to minimize the possibility of operating errors. Closing circuits of oil circuit breakers on generators and important tie lines are interlocked through the synchronizing receptacles. Closing circuits of the circuit breakers on major apparatus are interlocked through the hand reset auxiliary relays associated with the differential relays to prevent inadvertently reënergizing faulty equipment.

Testing of the switch house equipment and outgoing cables is facilitated through the provision of an induction voltage regulator-transformer set which will supply up to 30,000 volts. This set connects to a tets bus, which in turn can be used to energize the various circuits through disconnecting switches or in some cases, portable jumpers.

66-Kv Substation

The 66-kv substation is of the flat type with the bus insulators supported on steel pedestals as indicated in Fig. 4. All lines entering or leaving the substation are underground. The electrical arrangement involves duplicate busses with connections to each through an oil circuit breaker for all transformers and lines. The simplicity of the electrical connections permits a relatively simple physical arrangement.

The 66-kv busses are widely spaced to prevent any possibility of trouble on one affecting the other. As indicated by the cross section of the substation, the individual groups of selector equipment connecting to their respective busses are well spaced to insure maximum reliability. The conductors of each bus are on 8-ft centers, and the conductors of the circuits are on 6-ft centers. With the flat type of bus there are no structural parts above the busses, and a minimum of conductors crossing the busses on the individual circuits thus insuring a maximum degree of safety against bus short circuits from mechanical causes.

To provide for the contingency of a simultaneous conductor failure in each of the 2 parallel 66-kv lines to a substation, a transfer bus is installed so that one of the unfaulted conductors in one line can be connected in place of the faulted conductor in the other line, thus forming a complete circuit for emergency operation. The connections between the conductors in the lines and the single conductor transfer bus can be made by means of temporary jumpers when required.

Provision is made for the installation of bus sectionalizing reactors and oil circuit breakers should these be found desirable at some future date.

An interlocking arrangement through the use of keys is provided to prevent improper disconnecting switch operation. This includes the grounding switch facilities for the lines and busses, as well as the isolating disconnecting switches for the line equipment. A further precautionary feature includes padlocking the trip levers and mechanism housings of the 66-kv breakers. The keys for the individual locks are kept in the operating room. All of the equipment in the switch yard is clearly designated by prominent targets.

Testing of the 66-kv substation end of the outgoing cables is provided by means of a 300-kv kenetron (2-electrode hot-cathode vacuum tube) set which connects to a test bus. The various circuits may be connected to the test bus through disconnecting switches.

EXPERIENCE WITH BREAKER AND OTHER EQUIPMENT

At the time of installation of the isolated phase breakers and disconnecting switches some difficulty was experienced in getting proper alignment of parts and operation. Operating rods were weak mechanically, supports for toggles required bracing, balancing springs had to be installed to balance the weight of the rods, and other modifications were involved. However, it is probable that these troubles were such as might be expected with equipment located on different floors and tied together mechanically. The experience indicates that the parts for isolated phase equipment should be very carefully designed to minimize trouble.

Shortly after the station was placed in operation a fault occurred involving the failure of 4 of the individual oil switch phases and a considerable amount of other equipment. The trouble was due to a short circuit occurring on an outgoing 13.8-kv line which the breaker failed to open successfully and in the surging which followed another circuit broke down on a different phase giving the equivalent of a phase-to-phase short-circuit. As a result of this trouble, the breakers were modified by the manufacturers; also, some of the features previously mentioned in this paper were incorporated in the switch house design, particularly to prevent smoke from passing between floors.

There has been a considerable amount of trouble experienced with both the 13.8-kv and 66-kv oil circuit breakers during the period from the original installation to the present. A summary indicating the nature of the difficulties is given in Table II.

Table II—Classification of Troubles With 13.8-Kv and 66-Kv Oil Circuit Breakers

	13.8 Kv		66 Kv	
	Electrical	Mechanical	Electrical	Mechanical
Total	10	10	20	8
Design	8	2	19	7
Construction or defective material	2	8	1	1
Occurring during clearing of fault	5	0	15	5

The experience with the 13.8-kv breakers is based upon a total of approximately 560 breaker-years of service, and that with the 66-kv breakers on 80 breaker-years of service. In the case of the lower voltage breakers, most of the automatic operations have involved a relatively light duty due to the cable failures being mostly from one conductor to ground.

In the case of the 13.8-kv breakers, in addition to the serious trouble previously mentioned, there has been a certain amount of unfavorable experience while interrupting fault currents, principally excessive contact burning and carbonization of oil. There has also been the usual experience with mechanical features requiring readjustment or replacement from time to time.

Serious troubles have also been experienced with the breakers in the 66-kv substation. In one case a breaker bushing flashover resulted in damage to a considerable amount of adjacent equipment and interruption to one 66-kv bus.

In another case, in attempting to clear a line fault, a tank was blown off the breaker with a resulting oil fire which destroyed considerable equipment. This also resulted in a short circuit of one 66-kv bus.

After several cases of contact burning, oil carbonizing, and oil being thrown from the breaker, the breakers were rebuilt to improve their interrupting characteristics. Shortly after, one of the rebuilt breakers failed, resulting in a bushing being cracked, contacts pitted, oil carbonized, and general distress of the breaker. As a result of this experience, minor changes were made to the contact system and no difficulties of this nature have developed since.

In addition to the experience with the oil circuit breaker equipment there have been other scattered cases of trouble, such as the failure of a reactor in the switch house and undesirable expansion of the bus bars requiring the installation of expansion joints.

While the design was based upon accepted standards at the time of the original installation, evidence of high temperatures in the present 60,000-kw generator lead runs indicated the desirability of providing for movement of the copper to relieve the strain on the insulator supports. Leaf copper expansion joints suitably spaced with a fixed insulator between, together with springs under the bolts of the existing clamps have been installed to permit ample movement with temperature variation.

In connection with the installation of the 165,000-kw generator, most of the main bus conductor is being changed from a laminated to a copper channel construction to provide for the greater current. Channel construction also is being used for the connection from the new unit to the bus. The design includes provision for expansion in the copper members resulting from temperature variation both in the conductors and in the supporting structure. Expansion joints of leaf copper are provided at intervals with one fixed support between joints. The remaining supports are of the sliding type which permits the complete conductor assembly to move appreciably in either direction.

The installation of the large generator will necessitate modification to the switch house ventilation. The switch house is ventilated by a gravity system, utilizing for exhaust ducts the unused portion of vertical conductor compartments beyond the point where the conductor leaves the compartment at each isolated phase floor. With the increased generating capacity, a mechanical system will be required to dissipate the additional heat losses. The new system will consist of fans, one each in the up-river and down-river sections of each floor. Each blower will supply air to a distributing duct from which the incoming cold air will exhaust through discharge openings located near the floor line in the several equipment aisleways. The heated air will pass up through vertical compartments and dissipate through openings in the roof. Small fans will be installed, if experience shows them to be necessary, to circulate air through the main bus and new generator lead enclosures.

Conclusions

The experience with the Richmond switching facilities during the past 2 years, with the breakers modified to their present arrangement, indicates that an adequate and safe installation has been attained. Operation has been of a nature to give continuity of service and there have been no undesirable outages of individual circuits for which the switching facilities were responsible.

Ease of operation has been realized to a most satisfying degree, due primarily to the simplified arrangements provided for both the 13.8-kv and 66-kv layouts. It is believed that the straight double bus scheme with selector oil circuit breakers inherently gives maximum operating simplicity with maximum provision for reliability of service, and that the cost involved with such a layout is moderate for an important transmission and distribution center in a large metropolitan system.

At the time when Richmond Station was designed, experience throughout the country indicated that an isolated phase switch house would be most suitable for the purpose to be accomplished. Widespread experience obtained since the construction of Richmond station with switching facilities of various types is such, in the opinion of the authors, that there is some question as to whether the present type of isolated phase construction would be used in providing 13.8-kv switching facilities in excess of that which can be accommodated in the present switch house. It is rather difficult, and perhaps of little purpose, to predict what type of switching facilities will be provided in the future for Richmond or a similar installation. It is possible, however, that such facilities would be of the outdoor type. Of the various disadvantages of outdoor switching equipment, it is believed that the most serious is the possible damage from flying material in the event of failure of some piece of equipment. It seems that in many cases when equipment fails pieces of porcelain, oil, etc., may travel considerable distance; in fact, one case is known where relatively large pieces of porcelain traveled a horizontal distance of over 200 ft in an outdoor substation.

It is important that the development of switching facilities be such as to permit such installations being made at a lower investment cost than has been possible in the past. In the opinion of the authors standardization of oil circuit breakers, on which considerable work already has been done, should do much to accomplish this end. Just what other ways will be found to assist in bringing about a reduction in cost of oil circuit breakers is difficult to suggest. It may be that savings will be accomplished in the future in the application of circuit breakers by selecting breakers that will have an interrupting rating much lower compared to the calculated fault current than would be used according to the general practice today. To take full advantage of this suggestion apparently would require a complete knowledge of the magnitude of actual fault currents compared to the calculated values generally used for selecting oil circuit breakers. It would also be desirable to design the switchgear so that in the event of its failure to interrupt fault current, possibilities of serious damage would be eliminated. This apparently requires the use of circuit breakers that do not contain an inflammable fluid.

Considerable improvement has been made in the last few years in the technique relating to interruption of fault current, which has been largely responsible for the decreased time required to interrupt fault currents.

It is believed that the following features would be desirable to be kept in mind as further improvements in oil circuit breaker development:

1. Breakers should be capable of interrupting fault currents of any magnitude within their rating a number of times without requiring inspection or maintenance.

2. As mentioned above, it is highly desirable that the hazard from the use of inflammable fluid be eliminated.

3. It is believed that the bushings of oil circuit breakers should be improved in design and construction so as to better the performance of the oil circuit breaker as an interrupting device, and also to minimize the hazard due to flying pieces of porcelain in the event the bushing is disrupted at time of failure.

4. It should be possible to improve the oil circuit breaker as a mechanical device, so that there will be fewer adjustments and replacements required to keep it in satisfactory operating condition.

5. It would also be helpful if circuit breakers could be arranged so that the contact parts could be inspected and replaced with greater facility than is possible with the larger equipment at the present time.

Switching at the Connors Creek Plant

A description of the switching facilities at Essex station, adjacent to the Connors Creek generating plant of The Detroit (Mich.) Edison Company, is given this paper, which is part of a symposium on electric power switching at modern large steam-electric generating plants. Essex station, which has been in operation less than 2 years, has had an unusually good service record.

By
A. P. FUGILL
MEMBER A.I.E.E.

The Detroit Edison
Co., Detroit, Mich.

ESSEX, the switching station for the Connors Creek generating plant, is The Detroit Edison Company's most modern station. It was constructed in anticipation of the rehabilitation of the generating plant because the old switching station was inadequate for the increased generating capacity contemplated. The general system diagram of Fig. 1 shows the relation of Connors Creek to the rest of the system serving Detroit and vicinity, the installed generating capacity at each of the 4 steam generating plants, and the interconnections between them. By the fall of 1934, the Connors Creek plant will consist of 2 modern 30,000-kw turbine-generators, 2 45,000-kw units and 1 20,000-kw unit. The latter 3 are part of the original installation and will be replaced eventually by new machines. The expected future plant will consist of 2 30,000-kw and 3 90,000-kw units, although a total of 5 of the larger machines could be installed if conditions warrant.

When the design of Essex station was first considered, certain fundamental features were recognized as being highly desirable. These features may be outlined as follows:

1. The interrupting duty on the circuit breakers, with the ultimate generating capacity, should be kept within the rating of present-day circuit breakers by some scheme which would not interfere with the effective interchange of power between this station and the system.

2. All equipment in the station, particularly the circuit breakers, should contain a minimum of oil or compound. Experience had indicated that much of the serious damage in indoor switch houses was due to oil fires, and that oil circuit breakers were the most likely offenders.

3. All faults, including those directly on the bus, should be cleared rapidly and positively. Instantaneous relaying for feeder faults had been in use for many years but, until recently, no simple yet positive method was available for clearing bus faults promptly.

4. Bus fault currents should be kept to a predetermined, adequate path and not allowed to roam at will throughout the building. Two or 3 previous disagreeable experiences had shown that fault currents in the reinforcing rods could do considerable damage to the concrete at the most unexpected places.

5. The building construction should be entirely divorced from the electrical installation. Since 2 classes of workmen were required for these functions, it was felt that time and money could be saved if each class could complete its work without interference from the other group.

The detailed description of the Essex station given in this paper indicates that the fundamental design features mentioned above as being desirable have all been incorporated in the station as designed and built. The important features may be summarized as follows:

1. The connection diagram chosen provides fault current limitation without handicapping power interchange between the station and the system.

2. Possible damage from oil fires is reduced to a minimum by the use of *H*-breakers or deion breakers, air cooled reactors, and air insulated busses, and by the sectionalization of breakers in small rooms.

3. Rapid, positive clearing of bus faults is secured by enclosing all electrical equipment in isolated metal housings and by the associated bus fault relaying.

4. The bus fault current is kept to a predetermined path by the use of isolated metal housings and a low impedance ground network of copper and building steel.

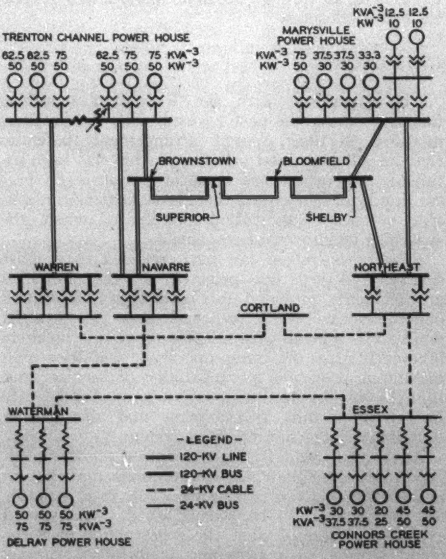

Fig. 1. General system diagram of The Detroit Edison Company

Full text of a paper recommended for publication by the A.I.E.E. committee on power generation, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23-26, 1934. Manuscript submitted Oct. 23, 1933; released for publication Nov. 23, 1933. *Not published in pamphlet form.*

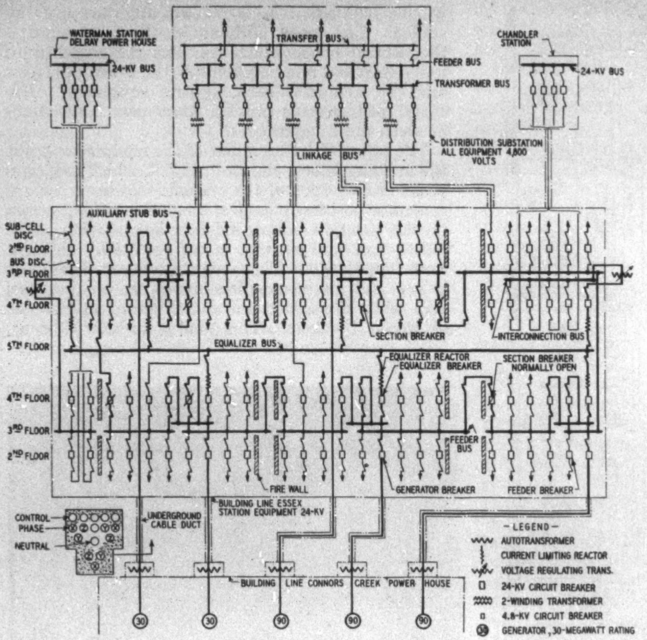
WATERMAN STATION DELRAY POWER HOUSE
24-KV BUS
TRANSFER BUS
FEEDER BUS
TRANSFORMER BUS
CHANDLER STATION
24-KV BUS
DISTRIBUTION SUBSTATION ALL EQUIPMENT 4,800 VOLTS
LINKAGE BUS
AUXILIARY STUB BUS
SUB-CELL DISC
2ND FLOOR
BUS DISC.
3RD FLOOR
4TH FLOOR
5TH FLOOR
EQUALIZER BUS
SECTION BREAKER
INTERCONNECTION BUS
EQUALIZER REACTOR
EQUALIZER BREAKER
SECTION BREAKER NORMALLY OPEN
4TH FLOOR
3RD FLOOR
2ND FLOOR
FEEDER BUS
FIRE WALL
GENERATOR BREAKER
FEEDER BREAKER
CONTROL
PHASE
NEUTRAL
UNDERGROUND CABLE DUCT
BUILDING LINE ESSEX STATION EQUIPMENT 24-KV
BUILDING LINE CONNORS CREEK POWER HOUSE
30
30
90
90
90
- LEGEND -
AUTOTRANSFORMER
CURRENT LIMITING REACTOR
VOLTAGE REGULATING TRANS.
24-KV CIRCUIT BREAKER
2-WINDING TRANSFORMER
4.8-KV CIRCUIT BREAKER
GENERATOR, 30-MEGAWATT RATING

Fig. 2. Connection diagram of Essex switching station with typical distribution substation

5. Metal housings and armored control cable permit the building construction and electrical installation to be distinct and separate operations.

Connection Diagram

The connection diagram for this station was chosen to coördinate with the type of distribution substation it was to serve. As indicated by Fig. 2, the typical substation is radially supplied, but the load busses are interconnected through reactors so that one supply feeder or more can be lost without any interruption to service. Inasmuch as only one feeder to the substation is supplied from each bus section at the switching station, the loss of a section of bus at Essex is of no more importance to the distribution substation than a transformer failure or a cable breakdown. Since, then, there is no necessity for double bus or double breaker, the connection diagram for the switching station combines the star-connected reactor or synchronizing bus scheme of fault current limitation with a simple, single bus and single breaker arrangement for individual feeders, but provides section breakers to obtain flexibility in the grouping of bus sections. Normally, bus sections are so combined that each generator supplies the load directly with as little interchange over the synchronizing or equalizer bus as is feasible.

This connection for reactors was preferred to a ring bus with intermediate reactors, to 2-winding generators, or to 3-winding transformers, because the system ties are equally available to all load in the station and, conversely, all generators are equally available to the system and to each other. Furthermore, the outage of a feeder bus does not cause the loss of any system ties.

Feeder reactors were discarded for the present because it was more economical to use a breaker of sufficient interrupting capacity than a smaller breaker and reactor. Furthermore, they are not necessary from the standpoint of reducing voltage disturbance on the bus because the fault is cleared so quickly. The design is such, however, that all feeders can be equipped with reactors if it should be necessary in the future.

The connection diagram of Fig. 2 shows that each generator, its autotransformer, and its 24-kv underground cables are considered as a unit and switched only at the switching station. Since multiple single-conductor cables are used, it is desirable to insure the proper division of current

Fig. 3. External view of Essex station

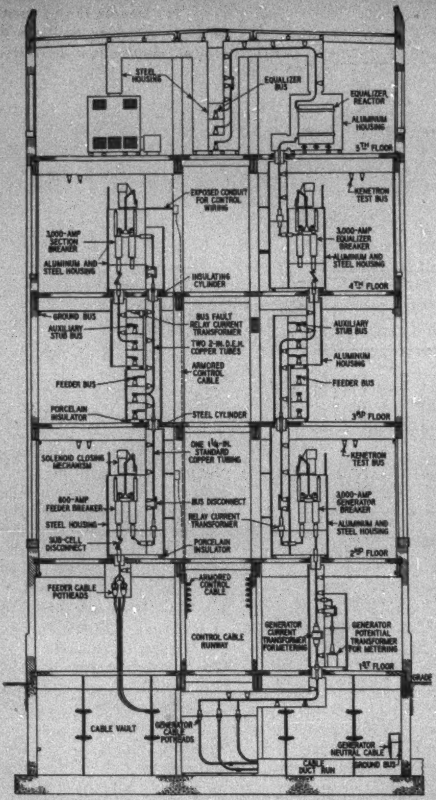
STEEL HOUSING
EQUALIZER BUS
EQUALIZER REACTOR
ALUMINUM HOUSING
5TH FLOOR
EXPOSED CONDUIT FOR CONTROL WIRING
KENETRON TEST BUS
3,000-AMP SECTION BREAKER
ALUMINUM AND STEEL HOUSING
3,000-AMP EQUALIZER BREAKER
ALUMINUM AND STEEL HOUSING
INSULATING CYLINDER
4TH FLOOR
GROUND BUS
AUXILIARY STUB BUS
BUS FAULT RELAY CURRENT TRANSFORMER
TWO 2-IN. D.E.H. COPPER TUBES
AUXILIARY STUB BUS
ALUMINUM HOUSING
ARMORED CONTROL CABLE
FEEDER BUS
FEEDER BUS
PORCELAIN INSULATOR
STEEL CYLINDER
3RD FLOOR
ONE 1¼-IN. STANDARD COPPER TUBING
SOLENOID CLOSING MECHANISM
KENETRON TEST BUS
800-AMP FEEDER BREAKER
BUS DISCONNECT
3,000-AMP GENERATOR BREAKER
STEEL HOUSING
RELAY CURRENT TRANSFORMER
ALUMINUM AND STEEL HOUSING
SUB-CELL DISCONNECT
PORCELAIN INSULATOR
2ND FLOOR
FEEDER CABLE POTHEADS
ARMORED CONTROL CABLE
CONTROL CABLE RUNWAY
GENERATOR CURRENT TRANSFORMER FOR METERING
GENERATOR POTENTIAL TRANSFORMER FOR METERING
1ST FLOOR
GRADE
CABLE VAULT
GENERATOR CABLE POTHEADS
GENERATOR NEUTRAL CABLE
CABLE DUCT RUN
GROUND BUS

Fig. 4. Composite cross section drawing of Essex station

among the cables of each phase. To accomplish this, the special, equilateral-triangle configuration of cables shown by the duct cross section on Fig. 2 was adopted. In addition, the neutral of the generator was grounded at the switch house through the neutral cable in the center of the triangle. This connection forces the fault current supplied over the phase cables by each generator to return by approximately the same path so as to reduce the voltage induced by these currents in the control cables and their sheaths. The control cables for each generator are carried in ducts directly above the main cable ducts but at no point are they exposed to the main cables.

PHYSICAL ARRANGEMENT

An outside view of the Essex switching station is shown in Fig. 3. The present building with its 68 feeder positions is adequate for a generating plant of 330,000 kw, but an extension to the right end will be required if 5 90,000-kw units are ever installed. The small building in the foreground is the control house which contains the switchboard for control and relay equipment, the control battery, and the kenotron cable testing equipment. Enclosed passageways provide convenient connections between the 2 buildings.

The physical arrangement of the equipment inside the building is best shown in Fig. 4, which is a composite cross section of the station, showing a typical generator position, equalizer breaker position, section breaker position and second-floor line position. The fourth-floor line position is not essentially different from that shown. The feeder busses, auxiliary stub busses, and interconnection busses are on the third floor while the second and fourth floors are devoted to circuit breakers. This double breaker-floor arrangement permits direct connections between breakers and busses and reduces the length of bus per breaker position. The symmetrical arrangement of equipment in horizontal cross section permits the location of breakers on outside walls of the building where large windows provide ample relief in case of serious explosion. The location of the equalizer bus and reactors on the fifth floor follows naturally from the breaker and bus arrangement. The fifth-floor equipment shown in the cross section drawing is not installed at present but will be as soon as the first 90,000-kw generator goes into service at the power house. The first floor is used, at present, only for the generator instrument transformers, feeder cable potheads, and the control cable runway. There is space, however, for the future installation

Fig. 5. Typical circuit breaker room on the outside building wall

of feeder reactors on the first and third floors, should they ever be required.

Two photographs of equipment housings are included to show the construction and method of insulating them from the building. A view of a typical breaker room on the outside wall of the building, Fig. 5, shows the breaker cells with the subcell disconnecting switch compartments underneath. The housings are mounted on porcelain insulators, the black insulating material shown being used to prevent smoke or gas from the breaker room traveling to other parts of the station and not for mechanical support. A view of the bus floor in one of the outer aisles, Fig. 6, shows the housings for feeder busses at the floor elevation and the housings for stub busses and aisle crossovers above them. The pothead housings for the feeder cables from the fourth-floor breakers are shown along the wall.

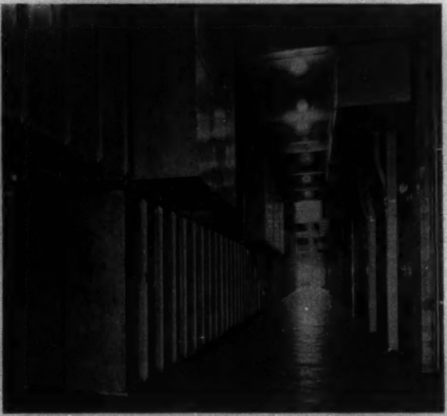

Fig. 6. Bus floor in the aisle on the outside building wall

CIRCUIT BREAKER EQUIPMENT

Pursuant to the policy of using equipment with a minimum of oil in the station, the design was laid out for the General Electric type *FH-209-C* circuit breaker which has only a small amount of oil in the pots. Before the station had been completed, however, the Westinghouse deion breaker with no oil entered the field, so a few of these breakers were purchased for a trial installation. In Fig. 7 is shown one of these deion breakers and the sub-cell disconnecting switches installed in the metal cell.

All breakers have an interrupting capacity of at least 40,000 amp, although the station design limits the calculated fault current any breaker will be required to interrupt to 35,000 amp or less. All feeder breakers are rated at 600 amp, and generator, equalizer, and section breakers are rated at 3,000 amp. Although operated on a 24-kv system, all insulation to ground, not only on these breakers but on all other electrical equipment in the station has a minimum flashover guarantee of 95 kv.

Since even the *H*-breaker contains sufficient oil to cause considerable smoke in case of an oil fire, the breaker floors are divided by fire walls into 7 breaker rooms per floor. In case of breaker trouble which fills a room with smoke so that the operator cannot make the inspection necessary before putting equipment back into service, only 9 breakers or less are involved. Furthermore, these breaker rooms are closed off from the center aisle where the disconnecting switches between the breaker and the bus are located, so that the operator could always pull these disconnecting switches even if he cannot get into the breaker room which is in trouble.

METAL HOUSINGS

One of the major features of this station is the use of metal housings for all electrical equipment. Each phase of the equipment is entirely metal enclosed by substituting metal for the conventional masonry construction in cells and bus walls. The complete housings rest on porcelain insulators to provide positive insulation from the building. In addition, they are grouped in units, each unit being definitely insulated from the others. Each bus section and its breakers form one unit, each auxiliary stub bus and generator breaker form another, the equalizer bus and reactors, a third, and each section breaker and equalizer breaker form a unit by itself. Thus, a fault in the station up to and including the feeder breakers must be a line-to-

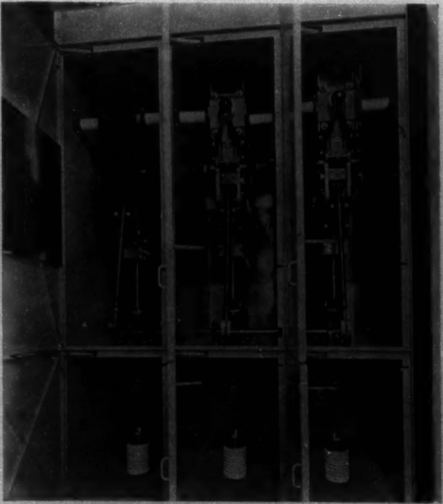

Fig. 7. Deion circuit breaker and sub-cell disconnecting switches in a metal housing

ground fault and the fault current can flow only to the isolated housing of the faulted equipment. It is a simple matter, then, to ground each unit of housing through a current transformer and provide relays to trip the proper breakers whenever current flows through this transformer.

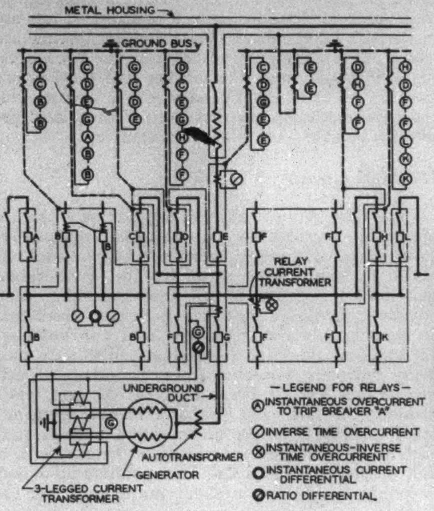
METAL HOUSING
GROUND BUS
RELAY CURRENT TRANSFORMER
UNDERGROUND DUCT
AUTOTRANSFORMER
GENERATOR
3-LEGGED CURRENT TRANSFORMER
—LEGEND FOR RELAYS—
Ⓐ INSTANTANEOUS OVERCURRENT TO TRIP BREAKER "A"
⊘ INVERSE TIME OVERCURRENT
⊗ INSTANTANEOUS-INVERSE TIME OVERCURRENT
○ INSTANTANEOUS CURRENT DIFFERENTIAL
⊘ RATIO DIFFERENTIAL

Fig. 8. Schematic diagram of protective relaying for typical bus sections

In this station, both steel and aluminum are used, depending upon the current capacity of the enclosed equipment. All 600-amp equipment uses steel entirely and, in general, 3,000-amp equipment uses aluminum. There is considerable steel, however, in the 3,000-amp breaker cells, and some steel bracing in the bus enclosures. Although the equalizer bus is designed for the same current as the other busses, its housing will probably be steel because of the low load factor. Each equalizer reactor will probably be enclosed in an aluminum cylinder with openings for self ventilation.

Several advantages can be claimed for metal housings in comparison with the conventional masonry type. They are lighter in weight but probably would not be as seriously damaged by an explosion or oil fire. Since they are built on jigs to precise dimensions, the joints are tighter and the clearances around doors and removable panels are smaller than is usually obtained with masonry construction, so that there is less chance of conducting gas entering the housing from an external source. They provide a means of keeping the current for a bus fault to a definite path away from the reinforcing rods in the concrete. Still more important, they are constructed as a unit in the shop so that erection in the station is a comparatively simple matter and does not interfere with the purely building operations. And, most important of all, they permit the fast, positive clearing of a bus fault by the use of simple overcurrent relays. Despite these advantages, the cost is slightly less than the conventional masonry type of construction.

FAULT PROTECTION

The relay protection for Essex station is outlined schematically in Fig. 8, which shows clearly the method of bus fault protection used with the isolated metal housings. Since each unit of housing is grounded at one point only, any fault current flowing to ground must pass through the current transformer in the ground connection. As many instantaneous plunger-type overcurrent relays as there are breakers to be tripped to clear a fault are connected in series to the secondary of this transformer. By using a separate relay for each breaker instead of a multicontact relay, accidental closing of the contacts of one relay will trip only one breaker. It is felt that this scheme of bus fault protection is so simple and positive, and the protective relays so rugged, that correct operation is practically assured. In another station, where this scheme is employed, one bus fault has occurred and the bus fault relaying performed perfectly.

Fig. 9. Control cable room located immediately under the switchboard

In Fig. 8 also is shown differential protection which is used on some of the larger machines at other stations and which probably will be used on the 90,000-kw units at this station. The winding on the middle leg of the 3-legged current transformer shown in the neutral end of the parallel-circuit generator winding provides sensitive protection on the generator itself. Normally, with equal currents in the 2 halves of the winding, no flux passes through the center leg of the core. If the currents are unbalanced, due to a fault in one half of the winding, some flux will pass through the middle leg and cause current to flow in the relay connected to the winding on that leg. Since the setting on the relay can be set low without danger of false operation, the protection for generator faults is very sensitive. Inasmuch as this scheme offers no protection for faults outside the generator, additional overall differential protection, including the transformer, underground cables, and generator breaker at the switch house, is provided by balancing the windings on the outer legs of the 3-legged current transformer against a current transformer on the generator breaker. Two sets of relays are used for this protection, each set tripping both the generator breaker and field breaker. Ratio differential relays, set as low as the transformer will permit, are depended upon for first-line protection but are backed up by the more rugged but less sensitive, instantaneous, plunger-type relays which are set high to prevent tripping due to slightly dissimilar current transformer characteristics.

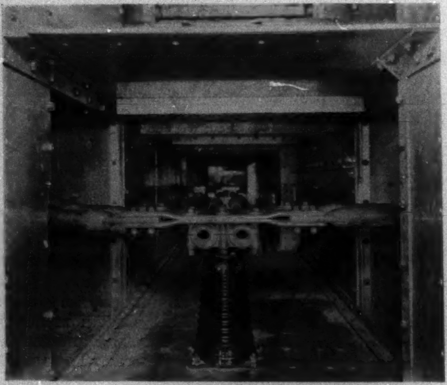

Fig. 10. One phase of bus with 2 3,000-amp taps

Fig. 11. Partial view of control room

Partly as back-up protection for the bus fault relaying, but mostly to clear the affected bus from the rest of the station in case a feeder breaker fails to open but does not cause a line-to-ground fault, the equalizer breakers are provided with time-delay overcurrent relay protection. It is possible to get selective action by the proper choice of the current setting on the relays, because the current through the equalizer breaker on the affected bus is divided approximately equally among the other equalizer breakers. For a fault on the equalizer bus, all equalizer breakers will trip if the bus fault relaying fails to operate.

The radial feeders have combination instantaneous time-delay relays to give instantaneous tripping for cable faults and time-delay for faults beyond the transformer in the distribution substation. The parallel circuits, which are mostly the system interconnection cables, have current differential relays to give instantaneous tripping when 2 lines are in service and overcurrent relays with inverse-time-limit characteristics for protection when only one line is in service.

ARMORED CONTROL CABLE

Another feature which simplified building construction considerably was the use of armored cable for control wiring instead of the conventional conduit buried in the walls and floors. With buried conduit, not only does the installation have to be coördinated with the building construction in an effort to avoid delays, but frequently, floors, particularly in the control room, have to be made thicker than necessary merely to accommodate the conduit. Since it is usually impossible to judge future needs accurately, extra conduit is installed just to be sure that there will be sufficient for the future. Even so, any change in plans causes considerable difficulty in revamping or extending the control system.

The use of armored control cable removes these difficulties. As employed at Essex, the method is comparatively simple. The control wiring from each breaker mechanism, relay transformer, and instrument transformer is carried in exposed conduit to a connection box on the nearest building column in the center aisle. By the use of a special construction at the floor joints, a duct the length of the column is provided between the fireproofing and the steel. The armored lead-covered control cables are carried in the duct from the connection box on the upper floor to the control cable runway on the first floor. This runway extends the length of the building and is connected to cross runways into the control house to provide access to the space under the switchboard. The cables are supported by clamp hangers in the columns and on racks in the horizontal runs. The routing is indicated in the cross-section diagram of Fig. 4 but a better conception of the installation can be obtained from Fig. 9, which shows the control cable room underneath the switchboard.

TYPE OF BUS

At the time this station was designed, there was considerable published information on the current rating of various types of busses in open air but little was available as to bus ratings when totally enclosed. Hence, tests were made to determine the rating of different types of flat-bar or round-tube bus when enclosed in a housing like that at Essex. It was found that, for the type of bus considered, a non-magnetic metal housing reduced the bus rating to about 75 per cent of that in open air while a magnetic housing reduced it still further to about 65 per cent.

On the basis of these tests, the bus of 2 double, extra-heavy copper tubes in parallel, used in this station, will carry 2,700 amp at 35 deg C rise above the ambient of the housing. A third tube can be added to increase the bus rating to 3,200 amp if it becomes necessary. Tubing was used instead of flat bar because it could be adapted more readily to a bus design which would stand the rather large mechanical stresses occasioned by the heavy fault currents at this station. One phase of the bus with 2 3,000-amp taps is shown in Fig. 10.

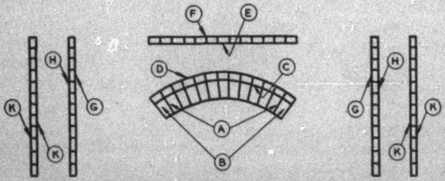

Fig. 12. Schematic floor plan of switchboard showing location of equipment

A. Generator controls, equalizer breaker controls, section breaker controls,
B. Interconnection breaker controls
C. Indicating meters
D. Bus fault relays
E. Bus fault relays, generator differential relays, recording meters
F. Bus fault relays
G. Feeder breaker controls
H. Bus fault relays
K. Feeder relays

With the equipment housing isolated from the building and grounded only through one connection to the ground bus, it is essential that this connection and the ground bus itself have a low impedance to ground or at least to the building steel in order to prevent excessive voltage on the housings. Hence, the connection from the housing was made as short as possible and a network of copper tubes and bars used for the ground bus. In addition, this bus was solidly connected to the building steel at frequent intervals so that it is impossible for much voltage to exist between the building steel and the ground bus. This arrangement takes advantage of the building steel, which is really a very low impedance network to ground, but still does not depend upon it entirely.

STEEL SWITCHBOARDS

The switchboard, as shown in the partial view of the control room in Fig. 11, is made up of cabinet-type steel panels, a benchboard for the generator controls, and a number of vertical boards for the feeder controls and relay equipment. The boards were all built and equipped in the shops of the company. They are totally enclosed with a hinged panel at the rear to provide access to the wiring and equipment terminals in a conventional manner. A schematic floor plan showing the arrangement of the panels and the location of the equipment on them is given in Fig. 12.

SERVICE RECORD

It is felt that the design of this station is such that any faults which can occur will be promptly and positively cleared. It would take a series of simultaneous failures in several pieces of equipment to cause loss of service to any important load, and such a series of coincidences is not likely to occur. To be sure, this particular station has operated less than 2 years but to date no trouble has been experienced. Furthermore, there are 4 other 24-kv switching stations on the system, incorporating most of the essential features of Essex station, which have been in operation for a total of 17 station years. The only case of a bus fault which has occurred is that mentioned previously and the protective equipment operated properly so that no interruption to load resulted. All faults on feeders out of these stations also have been properly cleared.

TRENDS IN DESIGN

Since the design of Essex station was based upon experience in the operation of such stations over a period of years, the developments in the art of switching in this company are incorporated in its design and exemplified by the features found in that station. To date, its operation and the operation of similar stations have not brought to light any situations which would cause a major change in design. As far as can be ascertained at the moment, if a new station, with the same function, were to be erected in the near future, it would be a virtual duplicate of this one in all its essential aspects. It is merely necessary to add, then, that the trend in the design of switching stations for modern generating plants as far as The Detroit Edison Company is concerned is most clearly indicated by referring to the foregoing description of Essex station.

Impulse Generator Circuit Formulas

With impulse voltage testing of electrical equipment becoming more widely used, it seems highly desirable to be able to calculate the circuit constants required to produce the desired test waves and to calculate the waves that any given circuit constants will give. In this paper the solution of the more commonly used impulse generator circuits is developed and summarized. Waves calculated by these formulas check closely the waves actually recorded by the cathode ray oscillograph.

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IMPULSE TESTING now has expanded from an experimental into a commercial field, and it is desirable that there be available a reliable and ready means of calculating the discharge or test waves of impulse generators to facilitate testing in this broadening field. Insulator time-lag characteristics usually are obtained for 0.5x5- and 1.5x40-μsec (defined later) waves, whereas to develop fully the internal oscillations in transformers long waves with steep fronts may be necessary; or to study the possibility of cumulative oscillations, the applied voltage should be oscillatory and of the same frequency as that of the apparatus tested. It is thus evident that to produce these specific waves and to make sure they are recorded on cathode ray oscillograms, it is necessary, if cut and try methods are to be avoided, to be able to calculate the circuit constants required to produce these waves and to calculate the test waves that these circuit constants give. In several articles[1,2,3,4] written at various times, the solutions for particular problems or particular circuits of the impulse generator have been shown. However, the rigorous solutions of many useful circuits probably never have been developed; hence in this paper the solutions of the more commonly used impulse generator circuits are developed and summarized.

Impulse Generator Circuit

The complete discharge circuit of the impulse generator, less charging equipment, is shown in Fig. 1, where, for convenience in analysis, it has been segregated into 4 distinct parts.

Part I represents the equivalent discharge circuit of the impulse generator proper. The capacitor units of the impulse generator (C) are usually of the oil filled type commonly used for power factor correction. They are compact, reliable, and readily procurable at reasonable cost. The discharge capacitance of the generator is that resulting from all the capacitors that discharge in series. The value of conductance G will depend primarily upon the values of the charging resistors in the circuit, but there may be also a small amount of leakage over the supporting frames to ground. The inherent resistance r of the impulse generator circuit, due to the resistance of the capacitors (0.01 to 1.00 ohm each), leads, and gaps, is ordinarily small, probably being less than 100 ohms even under transient skin effect conditions. The inherent series inductance L is due to the inductance in the capacitors (0.01 to 3.50 μh each) and to the inductive loops in the discharge circuit, this latter inductance being primarily a function of the length and configuration of the discharge circuit. A method of calculating it is shown in Appendix I. The terminal capacitance K includes the distributed capacitance of leads, capacitors, etc., to ground. Ordinarily it is too small to exert an appreciable influence on the wave applied to the test piece.

Part II of Fig. 1 shows the circuit for controlling

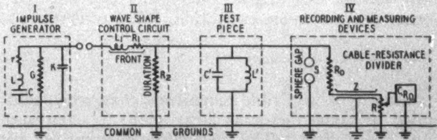


Fig. 1. Equivalent circuit of impulse testing equipment

C = generator capacitor units, arranged to be charged in parallel and discharged in series
G = leakage conductance of charging resistors and over generator frame (permits leakage of charge)
L = inherent inductance in generator circuit (retards wave front and causes oscillations)
r = inherent resistance in generator circuit (retards wave front, but not appreciably)
K = terminal capacitance due to gaps, leads, etc.
L_1 = inductance to retard wave front or to introduce oscillations
R_1 = resistance to control front of wave } depending also
R_2 = resistance to control duration of wave } on I and III
C' = effective capacitance of test piece (affects voltage crest appreciably, depending on I and II)
L' = effective inductance of test piece (affects wave duration appreciably and introduces oscillations)
S = sphere gap (measures voltage crests, except for extremely short waves)
R_0 = resistance of divider } determine voltage
Z = surge impedance of divider } reduction
R = Z = cable grounding resistor (potentiometer for CRO. R = Z prevents reflections)
CRO = cathode ray oscillograph

Full text of a paper recommended for publication by the A.I.E.E. committee on instruments and measurements, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Sept. 28, 1933; released for publication Dec. 4, 1933. *Not published in pamphlet form.*

[1] See bibliography at end of paper for numbered references.

the shape of the wave applied to the test piece. Were it not for this circuit, the wave shape would be determined by the constants of the impulse generator and the test piece, and a desired wave shape (such as a 1.5 x 40-μsec wave) might not be obtained. Both the series inductance L_1 and the series resistance R_1 tend, in general, to retard the length of the wave front. The inductance also will introduce oscillations in the wave and for this reason is usually made as small as possible. The shunt resistance R_2 controls to some extent the duration of the wave; in general for small loads, the duration varies directly with the shunt resistance.

Part III represents the test piece or load. Where the load is a bushing, an insulator string, or a gap, it may be represented by a capacitance. Ordinarily, the test piece capacitance will be between 50 and 400 $\mu\mu$f; to this must be added the stray capacitance of the leads which, depending upon the shape of the test circuit, may vary between 50 and 400 $\mu\mu$f. An ungrounded transformer also can be represented by a capacitance, and a single-winding transformer with one end grounded can be represented by a capacitance in parallel with an inductance and a resistance in series. From the kilovolt (*kv*) and kilovoltampere (*kva*) ratings of the transformer 2 of these constants can be approximated by simple relations. The inductance relation

$$L = \frac{10\,(\%\,\text{IX})\,(\text{kv})^2}{2\pi f\,(\text{kva})}\ \text{henries}$$

gives the equivalent inductance for the normal leakage reactance between 2 windings of a transformer. This inductance will have to be modified to suit the test arrangements, such as when the low voltage side of the transformer is connected to other apparatus for excitation. The resistance

$$R = \frac{10\,(\%\,I^2R)\,(\text{kv})^2}{(\text{kva})}\ \text{ohms}$$

is usually of negligible magnitude even when multiplied by some factor as large as 10 to compensate for skin effect. The capacitance may be considered in 2 parts: that of the bushing, which varies between 100 and 350 $\mu\mu$f; and that of the transformer winding, which varies between 200 and 1,000 $\mu\mu$f for ordinary transformers and is probably 10 times higher for shielded transformers.[5] The other capacitances to ground must be added, of course, to obtain the total load capacitance.

Part IV represents the recording and measuring devices. Both the sphere or other type of gap used to measure the test voltage and the divider resistance will have some capacitance to ground, which will add to the total load on the generator. The divider resistance also will offer another shunt resistance path to ground. The accuracy with which the test wave is recorded by the cathode ray oscillograph will depend to some extent upon how well the divider lead-in constants are balanced.[6] The cable grounding resistance R should be equal to the surge impedance Z of the lead-in cable to prevent reflections between the 2 when the divider resistance R_0 is large in comparison with Z, which is the usual case.[7] The small capacitance of the divider resistance and also the small capacitance of the cathode ray oscillograph deflector plates will not have an appreciable effect on oscillographs, except for chopped or peaked waves.[7, 8] The cable may damp peaked waves considerably, the attenuating effect increasing with the shortness of the peak and with the length of the cable.[8]

It is evident that the complexity of the complete circuit of Fig. 1 precludes a rigorous solution thereof, but fortunately the circuit may be simplified greatly for analysis and without sacrificing necessary accuracy. The extent to which simplification may be carried depends, of course, upon the relative values of the circuit constants of a given test arrangement. Moreover, the reason for ignoring certain constants may depend on test results or engineering judgment rather than on calculation. Thus, in its simplest form the discharge circuit of an impulse generator with a capacitance load can be represented by 5 circuit constants as shown in Fig. 2. The circuit constants L_1 and R_1 include both the added and the inherent inductance and resistance while the stray capacitance to ground of the connecting leads has been considered part of the load capacitance.

C_1 capacitance of impulse generator
L_1 total series inductance
R_1 total series resistance
R_2 shunt resistance
C_2 capacitance of test piece

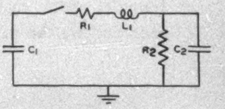


Fig. 2. Equivalent circuit of impulse generator

SOLUTION OF CIRCUIT

The shape of the voltage wave applied to the test piece can be obtained by calculating the impedance drop across the test piece. For illustrative purposes the circuit of Fig. 2 can be simplified into the circuit for eq 1 in Table I, by considering the load capacitance negligible; by Heaviside's notation the voltage drop across the resistance R_2 of that circuit is given by eq 1. This equation can be derived readily as follows:

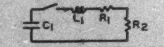
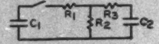
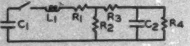
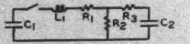
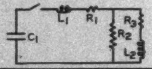
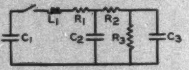
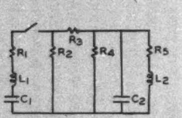
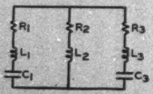
$$E = I\left(\frac{1}{pC_1} + pL_1 + R_1 + R_2\right)$$

$$E_{R2} = IR_2 = \frac{EA_0p\,1}{p^2 + A_{1p} + A_2}$$

The constant terms are defined in Table I. The solution of this equation can be obtained from a table of equivalent operators such as Bush's;[4] the particular form of the solution that will be used will depend upon whether the roots of the denominator are real or complex.

As more constants are placed in the impulse generator circuit, the solutions will become more complex. In the circuit for eq 2 of Table I the series inductance has been neglected, but the capacitance of the load has been considered and another resistance included. Ordinarily, most of the resistances that are in the series path with the load can be con-

Table I—Summary of Formulas for the Solution of Impulse Generator Circuits

Circuits	Equations		Constants
	$E_{R2} = I_{R2}R_2 = \frac{EA_0p1}{p^2 + A_1p + A_2}$	(1)	$A_0 = \frac{R_2}{L_1}$ $A_1 = \frac{R_1 + R_2}{L_1}$ $A_2 = \frac{1}{C_1L_1}$
	$E_{C2} = \frac{I_{C2}}{pC_2} = \frac{EB_0p\,1}{p^2 + B_1p + B_2}$	(2)	$B_0 = \frac{R_2}{C_2(R_1R_2 + R_1R_3 + R_2R_3)}$ $B_1 = \frac{C_1(R_1 + R_2) + C_2(R_2 + R_3)}{C_1C_2(R_1R_2 + R_1R_3 + R_2R_3)}$ $B_2 = \frac{1}{C_1C_2(R_1R_2 + R_1R_3 + R_2R_3)}$
	$E_{C2} = \frac{I_{C2}}{pC_2} = \frac{ED_0p1}{p^3 + D_1p^2 + D_2p + D_3}$	(3)	$D_0 = \frac{R_2}{C_2L_1(R_2 + R_3)}$ $D_1 = \frac{1}{C_2R_4} + \frac{R_1}{L_1} + \frac{L_1 + C_2R_2R_3}{C_2L_1(R_2 + R_3)}$ $D_2 = \frac{1}{C_1L_1} + \frac{R_1(R_2 + R_3 + R_4) + R_2(R_3 + R_4)}{C_2L_1R_4(R_2 + R_3)}$ $D_3 = \frac{1}{C_1C_2L_1(R_2 + R_3)} + \frac{1}{C_1C_2L_1R_4}$
	$E_{C2} = \frac{I_{C2}}{pC_2} = \frac{EF_0p1}{p^3 + F_1p^2 + F_2p + F_3}$	(4)	$F_0 = \frac{R_2}{C_2L_1(R_2 + R_3)}$
	$E_{C1} = \frac{I_{C1}}{pC_1} = \frac{EF_3(pC_2R_2 + pC_2R_3 + 1)1}{p^3 + F_1p^2 + F_2p + F_3}$	(5)	$F_1 = \frac{L_1 + C_2(R_1R_2 + R_1R_3 + R_2R_3)}{C_2L_1(R_2 + R_3)}$
	$E_{L1} = I_{L1}pL_1 = I_{C1}pL_1$ $= \frac{EF_4(p^3C_2R_2 + p^3C_2R_3 + p^2)1}{p^3 + F_1p^2 + F_2p + F_3}$	(6)	$F_2 = \frac{1}{C_1L_1} + \frac{R_1 + R_2}{C_2L_1(R_2 + R_3)}$ $F_3 = \frac{1}{C_1C_2L_1(R_2 + R_3)}$ $F_4 = \frac{1}{C_1(R_2 + R_3)}$
	$E_{R2} = \frac{EG_0(p^2L_2 + pR_3)1}{p^3 + G_1p^2 + G_2p + G_3}$	(7)	$G_0 = \frac{R_2}{L_1L_2}$ $G_1 = \frac{R_1}{L_1} + \frac{R_2}{L_1} + \frac{R_3}{L_2}$ $G_2 = \frac{1}{C_1L_1} + \frac{R_1R_2 + R_1R_3 + R_2R_3}{L_1L_2}$ $G_3 = \frac{R_2 + R_3}{C_1L_1L_2}$
	$E_{C3} = \frac{EH_0p1}{p^4 + H_1p^3 + H_2p^2 + H_3p + H_4}$	(8)	$H_0 = \frac{1}{C_2C_3L_1R_2}$ $H_1 = \frac{1}{C_2R_2} + \frac{1}{C_2R_3} + \frac{1}{C_3R_3} + \frac{R_1}{L_1}$ $H_2 = \frac{1}{C_1L_1} + \frac{1}{C_2L_1} + \frac{1}{C_2C_3R_2R_3} + \frac{R_1H_5}{L_1}$ $H_3 = \frac{R_1 + R_2 + R_3}{C_2C_3L_1R_2R_3} + \frac{H_5}{C_1L_1}$ $H_4 = \frac{1}{C_1C_2C_3L_1R_2R_3}$ $H_5 = \frac{1}{C_2R_2} + \frac{1}{C_2R_3} + \frac{1}{C_3R_3}$
	$E_{C2} = \frac{EK_0(p^2L_2 + pR_5)1}{p^4 + K_1p^3 + K_2p^2 + K_3p + K_4}$	(9)	$K_0 = \frac{R_3}{C_2L_1L_2(R_2 + R_3)}$ $K_1 = \frac{R_1 + K_5}{L_1} + \frac{K_6}{C_2} + \frac{R_5}{L_2}$ $K_2 = \frac{1}{C_1L_1} + \frac{1}{C_2L_1}\left[\frac{R_2(R_3 + R_4)}{R_4(R_2 + R_3)} + R_1K_6\right] + \frac{1}{C_2L_2} + \frac{R_5}{L_2}\left[\frac{K_6}{C_2} + \frac{R_1 + K_5}{L_1}\right]$ $K_3 = \frac{K_6}{C_1C_2L_1} + \frac{R_1 + K_5}{C_2L_1L_2} + \frac{R_5}{L_1L_2}\left[\frac{1}{C_1} + \frac{R_1K_6}{C_2} + \frac{R_2(R_3 + R_4)}{C_2R_4(R_2 + R_3)}\right]$ $K_4 = \frac{1 + R_5K_6}{C_1C_2L_1L_2}$ $K_5 = \frac{R_2R_3}{R_2 + R_3}$ $K_6 = \frac{R_2 + R_3 + R_4}{R_4(R_2 + R_3)}$
	$E_{C3} = \frac{EN_0(p^2L_3 + pR_3)1}{p^4 + N_1p^3 + N_2p^2 + N_3p + N_4}$	(10)	$N_0 = \frac{1}{C_3(L_1L_2 + L_1L_3 + L_2L_3)}$ $N_1 = \frac{L_1(R_2 + R_3) + L_2(R_1 + R_3) + L_3(R_1 + R_2)}{L_1L_2 + L_1L_3 + L_2L_3}$ $N_2 = \frac{R_1R_2 + R_1R_3 + R_2R_3}{L_1L_2 + L_1L_3 + L_2L_3} + \frac{C_1(L_1 + L_2) + C_3(L_2 + L_3)}{C_1C_3(L_1L_2 + L_1L_3 + L_2L_3)}$ $N_3 = \frac{C_1(R_1 + R_2) + C_3(R_2 + R_3)}{C_1C_3(L_1L_2 + L_1L_3 + L_2L_3)}$ $N_4 = \frac{1}{C_1C_3(L_1L_2 + L_1L_3 + L_2L_3)}$

sidered equal to zero if desired. As the denominator of eq 2 is of the second degree, its solution is similar to that of eq 1. The circuit for eq 3 is nearly the same circuit as that in Fig. 2, except that resistance R_3 is in series with the load and resistance R_4 shunts the load as would a divider resistance. This resistance is omitted in the circuit for eq 4; if R_3 of that circuit be considered equal to zero, there is obtained the circuit for Fig. 2 which is probably the most condensed circuit describing an impulse generator with a capacitance load. The solutions for eq 3 and 4 are similar and take the forms shown by equivalent operators 1 and 3 of Appendix III, the form of the solution depending upon whether the 3 roots obtained by equating the denominator to zero are all real or 1 real and 2 complex. The denominators of both eqs 3 and 4 are of the third degree. As there were no available published equivalent operators above the second degree, third-degree equivalent operators were developed; these are listed as Nos. 1 to 5 in Appendix III.

In eq 5 of Table I, only the transient terms of the numerator should be used if the voltage drop across the generator capacitance be required; but if the total voltage on the generator or the total current through it be desired, the total numerator of the right hand term should be used. The complete denominator is used, of course, in both cases. Equation 6 will give either the voltage drop across the series inductance or the current through it, according to its arrangement and solution.

The circuit for eq 7 has an inductive load rather than a capacitive load. As the denominator is of the third degree, its solution is similar to that of eq 4.

The circuit for eq 8 has an extra shunt capacitance to represent the stray capacitance of the generator and leads to ground. The denominator of this equation is of the fourth degree. As with the third-degree equations, there were no available published equivalent operators; therefore, fourth-degree equivalent operators were developed, these being listed as Nos. 6 to 16 in Appendix III.

The circuit for eq 9 shows an impulse generator with a transformer load, where the inductance of the transformer is in the discharge circuit to ground. In the circuit for eq 10 each part of the circuit contains inductance so that its position effect can be analyzed. The solutions of both these circuits are fourth-degree equivalent operators as shown in Appendix III.

These fourth-degree equivalent operators take 3 forms depending upon whether the 4 roots obtained by equating the denominator to zero are all real, 2 real and 2 complex, or all complex. The solving of these third- and fourth-degree equations to obtain the exponents shown in the final solutions in Appendix III may require appreciable time. However, these roots can be determined to as high a degree of accuracy as desired by various methods.

For a third-degree equation, the exact values of the 3 roots in terms of the circuit constants can be obtained by Cardan's formula. For equations of the third or higher degree and where only 2 roots of the equation are complex, Horner's method of extracting approximated roots is applicable. A method that is similar to Horner's method, but which seems to contain less chances for error and which seems easier of solution, is shown in Appendix II. In higher than third-degree equations which may or may not contain more than one pair of complex roots, the root-squaring method of Dandelin, Lobachevsky, and Graffe[9] of extracting roots is applicable.

WAVES RESULTING FROM CIRCUIT CALCULATIONS

The effect that each circuit constant has on the voltage wave applied to test piece can be shown best by varying each constant separately. The circuit constants of Fig. 2 representing an impulse generator with a capacitance load, were given practical values and by making a series of calculations their effects were shown. For an illustrative set of curves a practically smooth 1.5x40-μsec wave was used as the reference wave.

In this paper the first term of the impulse wave designation, as the 1.5 term, is the time in microseconds from zero time to the time of maximum crest; and the second term, as the 40 term, is the total duration in microseconds of the wave from zero time to the time of half crest amplitude on the tail or decreasing part of the wave. This "2-point" method of wave designation gives a good general description of the wave. The second term is used as the total duration of the wave from zero time to the time of half crest because it is determined easily when waves are calculated, and is easy to read from transcribed oscillograms because of the single time scale. When calculations are made the voltage equation takes the form of eq 3 in Appendix III, for example,

$$E = A[\epsilon^{-\alpha t} - \epsilon^{-\beta t} \{\cos \omega t + B \sin \omega t\}]$$

where A and B are constants. Suppose E_c is the crest voltage; then, since the oscillatory term usually becomes negligible long before the time to half crest is reached, the time t or the duration of the wave to half crest from zero time is given by

$$\frac{E_c}{2} = A\epsilon^{-\alpha t}$$

When the 2 terms of the wave are expressed as decimals, their exact values can be easily expressed and typed; and when the 2 terms are separated by a smaller letter "x," there is no confusion as to their meaning or limit, whereas a dash for separation might be taken as a range of values. This method of impulse wave designation is in accord with recommendations made by the lightning and insulator subcommittee of the A.I.E.E. committee on power transmission and distribution in a report presented at the 1933 A.I.E.E. winter convention (see "Recommendations for Impulse Voltage Testing," ELECTRICAL ENGINEERING, v. 52, January 1933, p. 17–22).

Figure 3 shows several waves containing different values of series resistance. As the series resistance is increased the oscillations are damped out and the magnitude of the crest is decreased. The front of the wave first decreases up to some critical value of series resistance, and then increases; but the duration of the wave seems to vary nearly directly with

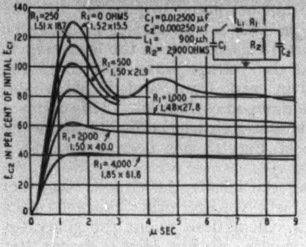


Fig. 3. Effect of varying R1 on wave shape

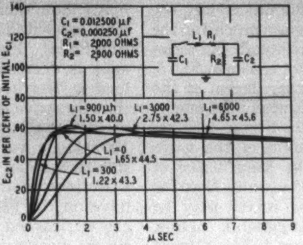


Fig. 5. Effect of varying L1 on wave shape

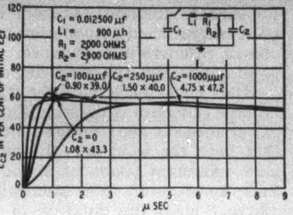


Fig. 7. Effect of varying C2 on wave shape

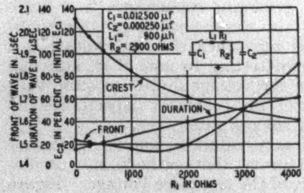


Fig. 4. Front, duration, and crest magnitude of wave vs. R1

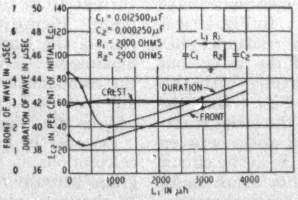


Fig. 6. Front, duration, and crest magnitude of wave vs. L1

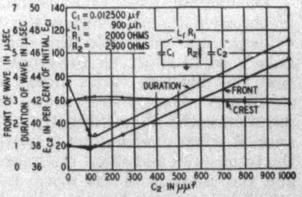


Fig. 8. Front, duration, and crest magnitude of wave vs. C2

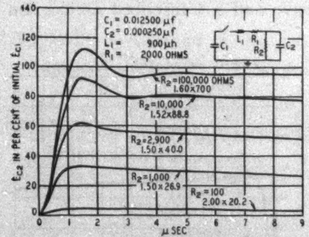


Fig. 9. Effect of varying R2 on wave shape

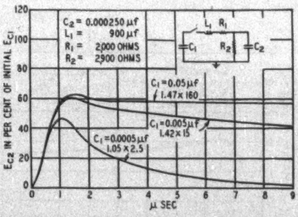


Fig. 11. Effect of varying C1 on wave shape

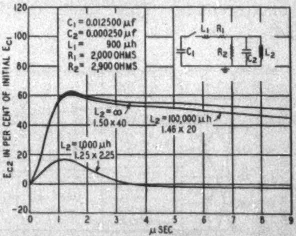


Fig. 13. Effect of varying L2 on wave shape

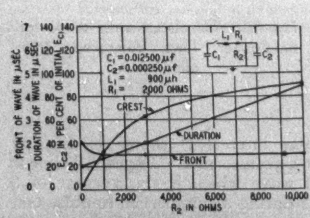


Fig. 10. Front, duration, and crest magnitude of wave vs. R2

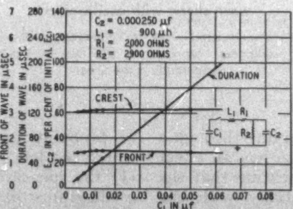


Fig. 12. Front, duration, and crest magnitude of wave vs. C1

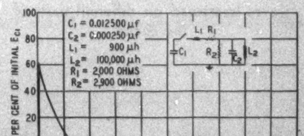


Fig. 14. 100,000-μh wave of Fig. 13 plotted to a smaller scale, showing that the wave is a damped oscillation

with the series resistance. This is shown clearly in Fig. 4. The crest variation also is shown in Fig. 4.

The series inductance was varied in Fig. 5 and the results are shown clearly in Fig. 6. Both the front and the duration of the wave have minimum values

Wave shapes calculated by means of formulas given in this paper (see Table 1). Circuit connections together with values of the circuit constants are indicated on each group of curves. All wave dimensions given are in microseconds as explained in the text

for slightly different values of inductance, but the crest magnitude does not seem to vary much for the chosen variation in inductance. Although the series resistance is high, the oscillating effect is seen in Fig. 5.

What might be termed the load regulation of the impulse generator is shown in Fig. 7, where the effects of variations in the load are shown. Figure 8 shows that both the front and the duration of the wave have minimum points at about the same value of load capacitance. It is interesting to note that for different loads the duration of the waves may be the same, but the front increases in general. Thus, waves with durations of 41 μsec have a 1-μsec front for a 60-μμf load and a 2-μsec front for a 350-μμf load. Figure 8 shows also that small variations in the load do not greatly affect the crest magnitude.

The damping effect that low shunt resistances have on the oscillations is shown in Fig. 9. In Fig. 10 it is evident that ordinarily the shunt resistance has only a small effect on the front of the wave, but that the duration varies almost directly with this resistance. Since it was shown in Fig. 4 that the duration varies almost directly with the series resistance, it seems evident that a relation exists between the total series and shunt resistance, R, in the circuit and the duration of the wave, t. For small loads, calculated waves and measured oscillograms show that the relation is $t \cong 0.7\ RC$. The constant C represents the capacitance of the generator, and if expressed in microfarads the time t is expressed in microseconds. This same relation exists in the simple circuit of a capacitance discharging through a resistance. The shunt resistance also has an effect on the crest magnitude, Fig. 10 indicating that the crest increases apparently exponentially with the resistance.

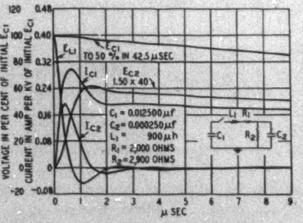


Fig. 15. Calculated wave shapes of waves impressed on different parts of the circuit

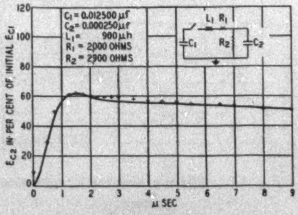


Fig. 16. Comparison of calculated wave shape with oscillogram

The calculated wave is 1.5x40 μsec; the oscillogram represented by the crosses apparently is the same

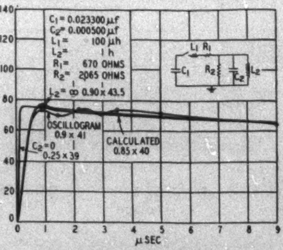


Fig. 17. Calculated wave shape for transformer load, compared with oscillogram

The fifth of the circuit constants to be considered is the capacitance of the impulse generator. Figure 11 shows that small variations in this capacitance do not alter the wave greatly. Figure 12 shows that the front and the crest are not changed appreciably by small variations in C_1, but that the duration varies nearly directly with C_1. This last observation is well expressed in the relation $t \cong 0.7\ RC$.

An inductance can be placed in parallel with the load capacitance so that a transformer load can be simulated. Figure 13 shows that as the load inductance is decreased the voltage wave applied to the load is decreased in crest, front, and duration, and that the wave is a damped oscillation. This damped oscillation effect is shown clearly in Fig. 14 where the 100,000-μh wave of Fig. 13 has been drawn to a smaller scale.

Besides showing the effects the circuit constants have on the test-piece voltage, other characteristics can be learned by calculations about the generator circuit during discharge. In Fig. 15 it is shown that at the first instant of discharge the entire voltage drop is across the series inductance; but this voltage drop soon decreases to zero and at that instant the current from the generator capacitance is a maximum. Figure 15 also shows that the charging current of the load is zero when the load voltage is a maximum. It is interesting to note that, although the components of the voltage drops are quite variable, the voltage of the generator capacitance decreases at a nearly smooth rate.

One of the primary values of impulse generator calculations is to prove that cathode ray oscillograms actually record the test-piece voltage. Figure 16 shows a calculated wave for a capacitance load and upon it is represented a transcribed oscillogram for the same circuit conditions. The 2 waves nearly coincide.

A calculated wave and a transcribed oscillogram of probably greater interest is shown in Fig. 17 where the load is a transformer. Figure 17 shows: (1) the measured wave which is the average of 3 oscillograms taken during a commercial impulse test on a power transformer; calculated waves; (2) neglecting the capacitance of the transformer load ($C_2 = 0$); (3) neglecting the inductance of the transformer load ($L_2 = \infty$); and (4) considering the inductance and capacitance of the transformer load. The close check between the oscillogram wave and the calculated wave where both the inductance and the capacitance have been considered shows the importance of considering the constants of the load added to the impulse generator, and the agreement that can be obtained between oscillograms and calculations when the calculations are made correctly.

Appendix I—Inductance of Generator Circuit

By means of 2 formulas from the Scientific Papers of the U.S. Bureau of Standards,[10] the inherent series inductance in the discharge circuit of the impulse generator can be calculated.

The leads and the banks of capacitors will form V-shaped paths, the inductance of which may be considered that of 2 parallel wires of radius p centimeters, of length h centimeters corresponding to the height of the V, and of distance d centimeters apart equal to half the base of the V. The formula for each V is then

$$L = 4h\left(\log_\epsilon \frac{d}{p} + \frac{1}{4} - \frac{d}{h}\right) \times 10^{-3} \text{ microhenries}$$

The inductance of these V's form about $^2/_3$ of the inherent series inductance of the generator.

The remainder of the inherent inductance of the generator is approximately equivalent to $^5/_8$ of the inductance of a square of sides a centimeters in length. For ease in computation the conductor is considered of square section and of α centimeters on a side. Small variations in α do not affect the total inductance greatly. The formula for the total inductance of the square is

$$L = 8a\left(\log_\epsilon \frac{a}{\alpha} + 0.477\frac{\alpha}{a} + 0.033\right) \times 10^{-3} \text{ microhenries}$$

Of course, approximately only $^5/_8$ of this inductance will be added to the inductance of all the V's in order to determine the total series inherent inductance of the impulse generator circuit.

Appendix II—Method of Root Extraction for Equations Containing Not Over 2 Complex Roots

Suppose a third degree equation be considered.

$$p^3 + k_2p^2 + k_3p + k_4 = 0 = (p - p_1)(p - p_2)(p - p_3)$$

Arrange the coefficients of the equation so that the first root can be obtained by a method similar to long division.

$$\begin{array}{llll|l}
1 + k_2 & + k_3 & & + k_4 & \underline{\alpha} \\
\alpha & + \alpha(k_2 - \alpha) & & + \alpha[k_3 - \alpha(k_2 - \alpha)] & \\
\hline
1 + (k_2 - \alpha) & + k_3 - \alpha(k_2 - \alpha) & & + \epsilon & \\
\alpha & + \alpha(k_2 - 2\alpha) & & & \\
\hline
1 + (k_2 - 2\alpha) & + [k_3 - \alpha(2k_2 - 3\alpha)] & & &
\end{array}$$

The nearer that k_4 minus $\alpha[k_3 - \alpha(k_2 - \alpha)]$ or ϵ approaches zero, the more accurate the roots of the equation will be determined. If the difference, ϵ, is zero, the remainder $1 + (k_2 - \alpha) + [k_3 - \alpha(k_2 - \alpha)]$ may be written as $1 + (A) + (B)$. This corresponds to the quadratic equation $p^2 + Ap + B = 0$ with solutions

$$p_2 = \frac{-A + \sqrt{A^2 - 4B}}{2}$$

and

$$p_3 = \frac{-A - \sqrt{A^2 - 4B}}{2}$$

These roots, of course, may be real or complex. The first root would have to be real, and as determined above would be $p_1 = -\alpha$.

As long as there are not more than 2 complex roots in an equation of any degree usually the real roots can be extracted in a manner similar to the method by which the root $p_1 = -\alpha$ was obtained.

In the preceding development, should ϵ not be equal to zero upon the first trial, the division process may be repeated and a second remainder obtained. This second remainder $[k_3 - \alpha(2K_2 - 3\alpha)]$ may be divided into ϵ to obtain a correction for α. If the correction be positive, it should be added to the first value of α to obtain a more nearly correct value of α. If the correction be negative, α is too large by approximately that amount and should be reduced

Appendix III—Equivalent Operators

Where $P_1 = -\alpha$, $P_2 = -\beta + \omega$, and $P_3 = -\beta - \omega$ for $n = 0, 1, 2$, or 3

$$\frac{P^n\,1}{P^3 + K_2P^2 + K_3P + K_4} = \frac{(-\alpha)^{n-1}\epsilon^{-\alpha t}}{(\alpha - \beta)^2 - \omega^2} + \frac{(-\beta + \omega)^{n-1}\epsilon^{(-B+\omega)t}}{2\omega(\alpha - \beta - \omega)} + \frac{(-\beta - \omega)^{n-1}\epsilon^{(-B-\omega)t}}{-2\omega(\alpha - \beta - \omega)} + R \quad (1)$$

$R = \frac{1}{K_4}$ for $n = 0$; $R = 0$ for $n = 1, 2$, or 3

Where $P_1 = \alpha$, $P_2 = -\beta + j\omega$, and $P_3 = -\beta - j\omega$

$$\frac{1}{P^3 + K_2P^2 + K_3P + K_4} = \frac{1}{(\alpha - \beta)^2 + \omega^2}\left[\frac{\epsilon^{-\alpha t}}{-\alpha} - \epsilon^{-\beta t}\left\{\frac{\alpha - 2\beta}{\beta^2 + \omega^2}\cos\omega t + \frac{(\omega^2 + \alpha\beta - \beta^2)}{\omega(\beta^2 + \omega^2)}\sin\omega t\right\}\right] + \frac{1}{K_4} \quad (2)$$

$$\frac{P^1}{P^3 + K_2P^2 + K_3P + K_4} = \frac{1}{(\alpha - \beta)^2 + \omega^2}\left[\epsilon^{-\alpha t} - \epsilon^{-\beta t}\left\{\cos\omega t + \frac{\beta - \alpha}{\omega}\sin\omega t\right\}\right] \quad (3)$$

$$\frac{P^2\,1}{P^3 + K_2P^2 + K_3P + K_4} = \frac{1}{(\alpha - \beta)^2 + \omega^2}\left[-\alpha\epsilon^{-\alpha t} - \epsilon^{\beta t}\left\{-\alpha\cos\omega t - \frac{\beta^2 + \omega^2 - \alpha\beta}{\omega}\sin\omega t\right\}\right] \quad (4)$$

$$\frac{P^3\,1}{P^3 + K_2P^2 + K_3P + K_4} = \frac{1}{(\alpha - \beta)^2 + \omega^2}\left[\alpha^2\epsilon^{-\alpha t} - \epsilon^{-\beta t}\left\{(2\alpha\beta - \beta^2 - \omega^2)\cos\omega t + \frac{\beta^3 - \beta^2\alpha + \beta\omega^2 + \alpha\omega^2}{\omega}\sin\omega t\right\}\right] \quad (5)$$

Where $P_1 = -\alpha$, $P_2 = -\beta$, $P_3 = -\gamma$, and $P_4 = -\delta$ for $n = 0, 1, 2, 3$, or 4

$$\frac{P^n\,1}{P^4 + K_2P^3 + K_3P^2 + K_4P + K_5} = \frac{(-\alpha)^{n-1}\epsilon^{-\alpha t}}{A_1} + \frac{(-\beta)^{n-1}\epsilon^{-\beta t}}{A_2} + \frac{(-\gamma)^{n-1}\epsilon^{-\gamma t}}{A_3} + \frac{(-\delta)^{n-1}\epsilon^{-\delta t}}{A_4} + R \quad (6)$$

$R = \frac{1}{K_5}$ for $n = 0$; $R = 0$ for $n = 1, 2, 3$, or 4

$A_1 = -\alpha^3 + \alpha^2(\beta + \gamma + \delta) - \alpha(\beta\gamma + \beta\delta + \gamma\delta) + \beta\gamma\delta$
$A^2 = -\beta_2 + \beta^2(\alpha + \gamma + \delta) - \beta(\alpha\gamma + \alpha\delta + \gamma\delta) + \alpha\gamma\delta$
$A_3 = -\gamma^3 + \gamma^2(\alpha + \beta + \delta) - \gamma(\alpha\beta + \alpha\delta + \beta\delta) + \alpha\beta\delta$
$A_4 = -\delta^3 + \delta^2(\alpha + \beta + \gamma) - \delta(\alpha\beta + \alpha\gamma + \beta\gamma) + \alpha\beta\gamma$

Where $P_1 = -\alpha$, $P_2 = -\beta$, $P_3 = -\gamma + j\omega$, and $P_4 = -\gamma - j\omega$

$$\frac{1}{P^4 + K_2P^3 + K_3P^2 + K_4P + K_5} = \frac{\epsilon^{-\alpha t}}{-\alpha A_5} + \frac{\epsilon^{-\beta t}}{-\beta A_6} + \frac{2\epsilon^{-\gamma t}}{A_7^2 + A_8^2}\left[\frac{(-A_7\gamma - A_8\omega)\cos\omega t + (A_7\omega - A_8\gamma)\sin\omega t}{\gamma^2 + \omega^2}\right] + \frac{1}{K_5} \quad (7)$$

$$\frac{P^1}{P^4 + K_2P^3 + K_3P^2 + K_4P + K_5} = \frac{\epsilon^{-\alpha t}}{A_5} + \frac{\epsilon^{-\beta t}}{A_6} + \frac{2\epsilon^{-\gamma t}}{A_7^2 + A_8^2}\left[A_7\cos\omega t + A_8\sin\omega t\right] \quad (8)$$

$$\frac{P^2\,1}{P^4 + K_2P^3 + K_3P^2 + K_4P + K_5} = \frac{-\alpha\epsilon^{-\alpha t}}{A_5} + \frac{-\beta\epsilon^{-\beta t}}{A_6} + \frac{2\epsilon^{-\gamma t}}{A_7^2 + A_8^2}\left[(-A_7\gamma + A_8\omega)\cos\omega t - (A_7\omega + A_8\gamma)\sin\omega t\right] \quad (9)$$

$A_5 = -\alpha^3 + \alpha^2(\beta + 2\gamma) - \alpha(\gamma^2 + \omega^2 + 2\beta\gamma) + \beta(\gamma^2 + \omega^2)$
$A_6 = -\beta^3 + \beta^2(\alpha + 2\gamma) - \beta(\gamma^2 + \omega^2 + 2\alpha\gamma) + \alpha(\gamma^2 + \omega^2)$
$A_7 = -2\omega^2(\alpha + \beta - 2\gamma)$
$A_8 = 2\omega(\gamma^2 - \omega^2 + \alpha\beta - \alpha\gamma - \beta\gamma)$

$$\frac{P^2\,1}{P^4 + K_2P^3 + K_3P^2 + K_4P + K_5} = \frac{\alpha^2\epsilon^{-\alpha t}}{A_5} + \frac{\beta^2\epsilon^{-\beta t}}{A_6} + \frac{2\epsilon^{-\gamma t}}{A_7^2 + A_8^2}\cdot$$

$$\left[\left\{A_7(\gamma^2 - \omega^2) - 2A_8\gamma\omega\right\}\cos\omega t + \left\{2A_7\gamma\omega + A_8(\gamma^2 - \omega^2)\right\}\sin\omega t\right] \quad (10)$$

$$\frac{P^4\,1}{P^4 + K_2P^3 + K_3P^2 + K_4P + K_5} = \frac{\alpha^3\epsilon^{-\alpha t}}{-A_5} + \frac{\beta^3\epsilon^{-\beta t}}{-A_6} + \frac{2\epsilon^{-\gamma t}}{A_7^2 + A_8^2}\cdot$$

$$\left[\left\{A_7\gamma(3\omega^2 - \gamma^2) + A_8\omega(3\gamma^2 - \omega^2)\right\}\cos\omega t + \right.$$

$$\left.\left\{A_7\omega(\omega^2 - 3\gamma^2) + A_8\gamma(3\omega^2 - \gamma^2)\right\}\sin\omega t\right] \quad (11)$$

Where $P_1 = -\alpha + j\omega$, $P_2 = -\alpha - j\omega$, $P_3 = -\beta + j\Omega$, and $P_4 = -\beta - j\Omega$

$$\frac{1}{P^4 + K_2P^3 + K_3P^2 + K_4P + K_5} = \epsilon^{-\alpha t}$$

$$\left[\frac{-(\alpha A_9 + \omega A_{10})\cos\omega t + (\omega A_9 - \alpha A_{10})\sin\omega t}{\omega(A_9^2 + A_{10}^2)(\alpha^2 + \omega^2)}\right]$$

$$+ \epsilon^{-\beta t}\left[\frac{-(\beta A_{11} + \Omega A_{12})\cos\Omega t + (\Omega A_{11} - \beta A_{12})\sin\Omega t}{\Omega(A_{11}^2 + A_{12}^2)(\beta^2 + \Omega^2)}\right]$$

$$+ \frac{1}{K_5} \quad (12)$$

$$\frac{P\,1}{P^4 + K_2P^3 + K_3P^2 + K_4P + K_5} = \epsilon^{-\alpha t}\left[\frac{A_9\cos\omega t + A_{10}\sin\omega t}{\omega(A_9^2 + A_{10}^2)}\right]$$

$$+ \epsilon^{-\beta t}\left[\frac{A_{11}\cos\Omega t + A_{12}\sin\Omega t}{\Omega(A_{11}^2 + A_{12}^2)}\right] \quad (13)$$

$$\frac{P^2\,1}{P^4 + K_2P^3 + K_3P^2 + K_4P + K_5} = \epsilon^{-\alpha t}$$

$$\left[\frac{-(\alpha A_9 - \omega A_{10})\cos\omega t - (\omega A_9 + \alpha A_{10})\sin\omega t}{\omega(A_9^2 + A_{10}^2)}\right] + \epsilon^{-\beta t}$$

$$\left[\frac{-(\beta A_{11} - \Omega A_{12})\cos\Omega t - (\Omega A_{11} + \beta A_{12})\sin\Omega t}{\Omega(A_{11}^2 + A_{12}^2)}\right] \quad (14)$$

$A_9 = 2\omega(\alpha - \beta)$
$A_{10} = (\Omega^2 - \omega^2) + (\alpha - \beta)^2$
$A_{11} = 2\Omega(\beta - \alpha)$
$A_{12} = (\omega^2 - \Omega^2) + (\alpha - \beta)^2$

$$\frac{P^3\,1}{P^4 + K_2P^3 + K_3P^2 + K_4P + K_5} = \frac{\epsilon^{-\alpha t}}{\omega(A_9^2 + A_{10}^2)}$$

$$\left[\left\{A_9(\alpha^2 - \omega^2) - 2A_{10}\alpha\omega\right\}\cos\omega t + \left\{2A_9\alpha\omega + A_{10}(\alpha^2 - \omega^2)\right\}\right.$$

$$\left.\sin\omega t\right] + \frac{\epsilon^{-\beta t}}{\Omega(A_{11}^2 + A_{12}^2)}\left[\left\{A_{11}(\beta^2 - \Omega^2) - 2A_{12}\beta\Omega\right\}\cos\Omega t + \right.$$

$$\left.\left\{2A_{11}\beta\Omega + A_{12}(\beta^2 - \Omega^2)\right\}\sin\Omega t\right] \quad (15)$$

$$\frac{P^4\,1}{P^4 + K_2P^3 + K_3P^2 + K_4P + K_5} = \frac{\epsilon^{-\alpha t}}{\omega(A_9^2 + A_{10}^2)}$$

$$\left[\left\{A_9(-\alpha^3 + 3\alpha\omega^2) + A_{10}(3\alpha^2\omega - \omega^3)\right\}\cos\omega t + \right.$$

$$\left.\left\{A_9(\omega^3 - 3\alpha^2\omega) + A_{10}(-\alpha^3 + 3\alpha\omega^2)\right\}\sin\omega t\right] +$$

$$\frac{\epsilon^{-\beta t}}{\Omega(A_{11}^2 + A_{12}^2)}\left[\left\{A_{11}(-\beta^3 + 3\beta\Omega^2) + A_{12}(3\beta^2\Omega - \Omega^3)\right\}\right.$$

$$\left.\cos\Omega t + \left\{A_{11}(\Omega^3 - 3\beta^2\Omega) + A_{12}(-\beta^3 + 3\beta\Omega^2)\right\}\sin\Omega t\right] \quad (16)$$

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Portable Schering Bridge for Field Tests

A portable Schering bridge which is applicable for power factor, dielectric loss, and capacitance tests on condenser bushings and other equipment of higher capacitance in the field is described in this paper, and operating procedure is given. Such tests are desirable for forestalling failures of equipment. Although earlier power factor tests on bushings have been made in the field, this is probably the first application of the Schering bridge to field tests.

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THE attention given to bushings in service has not kept pace with the increasing service demand throughout the years. This is not negligence on the part of the operating companies, as they have always serviced bushings by the best available means. Generally a bushing has been put into service and operated for life, or until it failed, with only routine surface inspection. The change of apparatus from indoor to outdoor operation, the

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steady increase of line insulation to prevent circuit flashover, the extension and interconnection of lines have subjected bushings to higher and more frequent overvoltages.

The effort expended by operating companies to inspect and service apparatus in order to give to the public reliable and continuous service warrants a more effective test for bushings than has been available in the past. Dielectric loss measurements detect deterioration of insulation which might later cause failure. However, a portable instrument for the measurement of dielectric loss was not available for purchase and use by the power companies until the Schering bridge here described was developed. Although designed primarily for power factor, dielectric loss, and capacitance tests on condenser bushings in circuit breakers and transformers, this portable Schering bridge also is adaptable to the testing of equipment of higher capacitance, such as cables, and for miscellaneous laboratory uses.

CONSTRUCTION FEATURES

In Fig. 1 is shown a schematic diagram of the apparatus, which is a Schering bridge designed for "inverted" operation, to permit testing capacitors having one terminal grounded. The testing potential is 13.8 kv, which has been found adequate for finding faults, even in 230-kv bushings.

In Fig. 2 is shown the experimental model of the portable inverted Schering bridge, as used in obtaining the results herein reported. The manually operated decade resistors, decade capacitors, shield balancing controls, galvanometer, and all the parts which in conventional laboratory bridges are very near ground potential, are at 13.8-kv potential from ground in this set. Therefore, they are enclosed in a metal box or shield which is balanced to galvanometer potential, and this box is enclosed in a grounded box. The knobs on the front panel are connected to their respective instruments by insulating shafts which have metallic bearings on the inner panel or shield to prevent shaft leakage currents from entering the bridge circuit. In the experimental unit, Fig. 2, the lower cabinet contains a small air cooled testing transformer, a panel of switches and signal lamps, and a cylindrical standard air capacitor of 165 μμf.

A new design, now built, includes a no-loss standard capacitor in the upper cabinet which utilizes the capacitance between the inner and outer boxes. A strip around the ends, top, and bottom of the inner box comprises the active electrode, while the front and back serve as guard rings. The transformer and the low voltage switching are mounted on the table which supports the instrument case, as shown in Fig. 3.

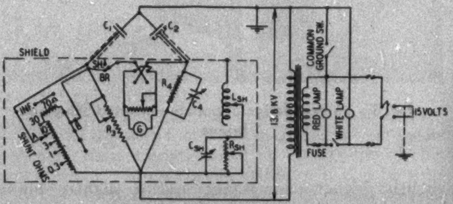


Fig. 1. Schematic diagram of complete circuit (except film cut-out)

Shunt switch points A and B are always opposite, being moved by same knob

The cable which connects the set to the high voltage terminal of the capacitor under test has an inner shield which is balanced to the same potential as the central wire, thus eliminating losses from wire to shield; and also has an outer shield which is grounded.

A reflecting vibration galvanometer is used because of its simplicity and its sensitivity to the fundamental frequency only.

If desired, the set can be made convertible for use in the conventional laboratory manner (i. e., not inverted, but with ground at instrument end) for testing at voltages above 13.8 kv, with auxiliary standard capacitor and transformer designed for the voltage to be used.

OPERATION

The inverted Schering bridge is operated in the same manner as the conventional laboratory type.

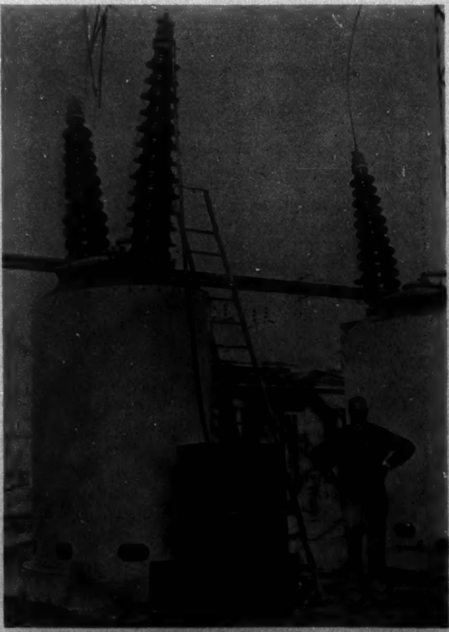


Fig. 2. Experimental model of the portable inverted Schering bridge used in obtaining the results given in this paper

Referring to Fig. 1, the galvanometer switch is turned to the shield position and the shield is balanced approximately by manipulation of the shield impedance, R_{SH}, L_{SH}, and C_{SH}. Then the galvanometer switch is turned to the bridge position, and balanced to a null reading by simultaneous manipulation of the decade resistors R_3 and the decade capacitors C_4. In most bushing tests the shield impedance can be shorted out entirely without appreciable error in readings, but in testing insulation samples of very small capacitance or very low power factor it is necessary to balance the shield if high accuracy is required.

The existence of interference affecting only the galvanometer, such as an alternating current magnetic field, can be detected by turning the galvanometer reversing switch. Such interference is nearly always negligible, but if not the bridge can be rebalanced with the galvanometer reversed, and the readings averaged.

Errors due to interference from an electrostatic field, such as from a high voltage line overhead, can usually be eliminated by averaging readings taken with the 115-volt supply line reversed, but occasionally special shielding may be required.

In the following equations, the symbols used are:

C_{1s} = equivalent series capacitance of the specimen
C_{1p} = equivalent parallel capacitance of the specimen
C_2 = fixed capacitance of standard air capacitor
C_4 = decade capacitor microfarads. (Range 0 to 11.111)
R_3 = decade resistor ohms. (Range 0 to 1111.11)
R_4 = fixed resistor ohms. $\frac{(100{,}000)}{2\pi f}$
Y = shunt ohms, indicated at shunt switch-point. (0.3, 1, 3, 10, or 30)
θ = phase angle. ($\cos\theta$ = power factor)

When the bridge is balanced:

$$\frac{C_4}{10} = \cot\theta$$

Specimens tested with less than 50 ma charging current (i. e., C_{1s} less than 9,600 $\mu\mu$f for 13.8-kv 60-cycle test) do not require the use of a shunt across R_3, and the shunt switch is placed at the "INF." point; then

$$C_{1s} = C_2 \frac{R_4}{R_3}$$

For specimens of larger capacitance,

$$C_{1s} = C_2 R_4 \frac{100 + R_3}{YR_3}$$

The total resistance from the galvanometer terminal to the end of the shunts is 100 ohms. Although part of this resistance is connected in series with the specimen when using the shunts, its effect on the power factor of the specimen is negligible.

$$C_{1p} = C_{1s} \sin^2\theta$$

For low power factors it is permissible to assume

$$C_{1s} = C_{1p} \text{ and } \cos\theta = \cot\theta$$

Ordinarily no correction is required for power factors less than 0.10. In practice a correction curve is used which shows values of power factor and $\sin^2 \theta$ corresponding to any value of C_4.

The proofs of the above statements are not given here, having been covered in previous Schering bridge literature. (See "Alternating Current Bridge Methods," by B. Hague, Sir Isaac Pitman and Sons, Ltd., revised, 1930; and "Testing High-Tension Impregnated Paper-Insulated, Lead-Covered Cable," by E. S. Lee, A.I.E.E. TRANS., v. 44, 1925, p. 104–16.)

It will be noted that the inverted bridge, Fig. 1, and the ordinary laboratory bridge, will not give exactly the same readings on the same condenser bushings when tested in the laboratory. The inverted bridge always reads the total capacitance between the high voltage terminal of the bushing and ground, which includes, in parallel with the internal capacitance of the bushing itself, the external capacitance from the high voltage ends of the bushing to all surrounding grounded objects. In the ordinary laboratory bridge circuit, the flange of the bushing is not grounded and the bridge reads the internal capacitance of the bushing plus the external capacitance from the flange to the ends of the bushing and the high voltage lead connected thereto. Thus the readings by the inverted bridge show a slightly higher capacitance and a slightly lower power factor than is shown by the ordinary laboratory arrangement, but the difference is small. For example, a 66-kv bushing, set up in a vertical position on a wooden stand in the laboratory, measured 0.0115 power factor, 149.0 $\mu\mu$f by the in-

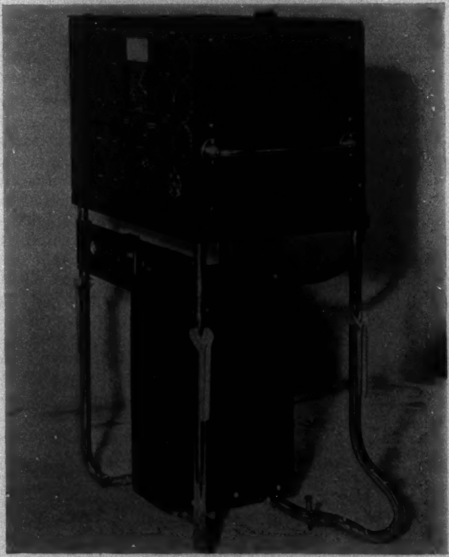


Fig. 3. A new design of portable inverted Schering bridge

verted Schering bridge, and 0.0134 power factor, 137.3 μμf by the same bridge used noninverted and also by a laboratory Schering bridge.

When the bushing is tested in its tank, the capacitance read by any method is that of the bushing plus its capacitance to tank wall, etc., and is not a true capacitance of the bushing. The small error due to inversion is therefore of no importance.

For laboratory work or where extreme accuracy is desired, the test specimen can be shielded so that both the error in capacitance and the error in power factor practically disappear.

ACCURACY, SENSITIVITY, AND RANGE

The accuracy of the bridge is dependent upon the accuracy of the calibrated resistors and capacitors, and also to a very large extent upon the proper shielding of the specimen.

The sensitivity is sufficient to read at least 3 significant figures in power factor and 4 significant figures in capacitance. The sensitivity depends upon the test voltage, the galvanometer, and the values of C_2, R_3, R_4, and C_4, and is not affected by the inversion of the circuit.

The range in power factor is from 0.0000 to about 0.7432 (i. e., to $\cot\theta = 1.111$). The minimum capacitance readable is determined by the capacitance of the standard C_2, the maximum resistance of R_3, and the frequency. For the bridge now being built the minimum is $C_{1S} = C_2 \dfrac{R_4}{R_3} = 200\ \mu\mu f \times \dfrac{100{,}000}{2\pi f \times 1{,}111.11 \text{ ohms}} = 200\ \mu\mu f \times \dfrac{90}{2\pi f} = \dfrac{18{,}000}{2\pi f}$. This minimum C_{1S} is therefore 47.8 μμf at 60 cycles, 57.3 μμf at 50 cycles, and 114.6 μμf at 25 cycles. The maximum readable capacitance is determined by the current carrying capacity of the testing transformer and the shunts for the R_3 arm of the bridge.

The shunts in these sets, as ordinarily built, have a maximum current rating of 10 amp.

The field set uses a potential transformer. A larger transformer is required when the shunts are needed.

GENERAL QUESTIONS OF BUSHING TESTS

Although the value of a-c loss tests for investigating insulation characteristics has been known for a long time, a test of this nature has been used as a field test only in recent years.

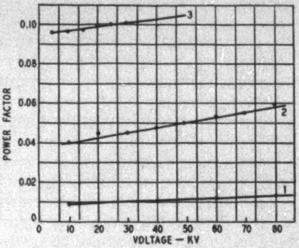
There may be some question raised as to the reliability of a power factor taken at 13.8-kv on bushings that have normal operating voltage above this test voltage. From curves in Fig. 4 it can be seen that the power factor change with increased voltage is not erratic, but is a gradual increase from 10 kv to voltage above the normal rating of the bushings. The curves show that the higher the power factor the greater is the change in power factor with increasing voltage. The curves show that a test at 13.8 kv is a very fair representation of the bushing loss at rated voltage. Wherever a test has shown a defective bushing at normal operating voltage, the bushing also has been shown defective on the 13.8-kv test.

Fig. 4. Power factor versus test voltage

Curve 1. 66-kv bushing. Operating voltage 39.9 kv

Curve 2. 115-kv bushing. Operating voltage 66.4 kv.

Curve 3. 34.5-kv bushing. Operating voltage 19.9 kv

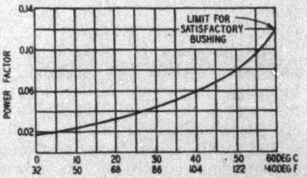


There is an increase in power factor with increase of temperature and the higher the power factor the more rapid is the increase. The power-factor-temperature curve in Fig. 5 was created from laboratory investigations and has been used in our field tests for interpreting the test results on the condenser type bushings. We would expect any condenser bushing having a power factor falling on or below the curve to meet the standard one minute acceptance test. The curve has not been used as a sharp dividing line between what constitutes a good and a poor bushing. A bushing with a power factor approaching or extending slightly beyond the curve was held in suspicion, and the procedure taken depended upon whether periodic tests were to be made, whether the bushing was located where an interruption meant serious trouble, or whether the type of bushing had materials which might have inherent high losses. With all the data already obtained by the different companies, it will probably be several years before a fairly definite statement can be made as to the power factor which represents a satisfactory bushing for service. The power factor tests may eventually show the best results when interpreted on a comparison basis; that is, tests made

Fig. 5. Power factor limits for condenser bushing

Condenser bushings with power factors on or below curves are believed to be satisfactory. Immediately above curve and of uncertain height is a doubtful zone in which bushings are probably satisfactory

Tests should be made with the bushing disconnected from all lines
Testing when bushing is below 60 deg F is not recommended



periodically and compared with previous tests to show any changes which may have taken place. Comparisons with similar bushings will also be of value. A high power factor may be the natural power factor of the bushing, and if the power factor remains constant, satisfactory service should be expected. In other words, a 0.03 to 0.04-power factor bushing that remains constant from year to year may be safe, whereas a bushing that changes from 0.01 or 0.015 power factor to 0.025 or 0.03 power factor may be unsafe.

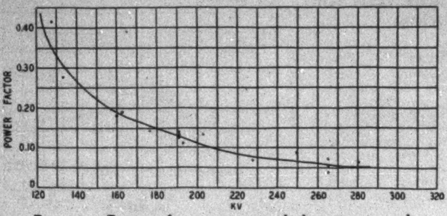


Fig. 6. Power factor versus dielectric strength

Power factor-voltage curve on experimental bushings of the same physical dimensions is shown

Power factor values were at 100 deg C

Voltage test with lower end of bushing in 70 deg C oil 130 kv applied for 10 hr and raised 15 kv each succeeding 10 hr

The majority of bushing troubles are due to moisture entering the bushing. In most types of bushings the process of deterioration caused by the moisture is slow, and it is the authors' opinion that the presence of moisture in a bushing can be determined by the power factor test long before it reaches a dangerous condition. As power factor is more pronounced at higher temperatures it is preferable to make the test at a time when the temperature of the apparatus is not lower than 60 deg F.

METHODS OF TESTING CIRCUIT BREAKERS IN THE FIELD

To test a circuit breaker, the leads are disconnected from the bushings at the top and the lead from the testing set is attached. Tests are made with the breaker closed, and then on each bushing by itself with the breaker opened. The combined readings give a definite story of the insulating condition of the oil, lift rods, and bushings of the breaker.

Testing without disconnecting the bushing from the lead to the disconnecting switch is faster, but has disadvantages which lessen the value of the bushing test. *First*, the disconnecting switch loss is included in the test. *Second*, the pick-up interference on the disconnecting switch and the lead between the bushing and the switch affects the reading, and makes it necessary to obtain a value from the average of 2 readings taken by reversing the 115-volt line to the testing set. *Third*, the capacitance of the bushing is not obtained. The capacitance of the bushings should be watched as closely as the power factor values. If the bushing is partly punctured and the punctured path charred so as to be conducting, the power factor will read normal. The capacitance will increase, and it is the capacitance which must be depended upon to detect the partial failure. *Fourth*, the comparison between tests is made difficult and uncertain.

An abnormal reading from a bushing tested alone, in the breaker, indicates bushing faults. Abnormal readings from both bushings, when tested separately on the same breaker unit, indicate both bushings at fault, or more likely high power factor oil. Normal readings on the bushings in a unit, and abnormal readings from the unit with breaker closed indicate lift rod and guide trouble.

PROCEDURE FOR LOCALIZING THE CAUSES OF ABNORMAL VALUES

If indications are that the bushing is at fault the following steps are taken. After each step the power factor test is repeated.

1. The exposed porcelain is shielded to eliminate surface leakage.
2. The oil is dropped in the circuit breaker and the porcelain arc shield surface is cleaned.
3. The porcelain arc shield is removed and the oil end of the bushing cleaned. If there is any question of the condition of the oil in the arc shield chamber, power factor and dielectric breakdown tests are made on it.

If the values are not reduced to normal by procedures 1, 2, or 3, above, the insulation of the bushing is at fault and the bushing is removed from service for reconditioning or salvaging.

The capacitance of a bushing is slightly higher in a breaker than when tested alone. The increase of capacitance is caused by the presence of tank wall and the contact parts. This increase in capacitance is very consistent for breakers of the same type and voltage class.

The power factor value with the breaker closed is generally found to be nearer that of the bushing with the lower power factor, rather than equalling the mean power factor of the 2 bushings. If the oil or lift rods have appreciable loss the above is not true and the power factor with breaker closed may become any greater value.

If indications are that the oil is at fault:

1. Power factor and dielectric breakdown tests are made on samples of the oil.
2. An analysis of the oil is made.
3. The oil is reconditioned or replaced with other oil.

Notes: New oil has a power factor well under 0.005. The tests have indicated that good oil from service measures less than 0.01 power factor at 20 deg C.

If indications are that the lift rod and guides are at fault:

1. The oil is dropped in the circuit breaker and the lift rod and guide are given a surface examination and tested for leakage paths with a megger.
2. The parts are cleaned and reëxamined and re-meggered.
3. The circuit breaker is closed and power factor retaken.

If the values cannot be brought to normal the lift rods or guides should be replaced. All lift rod and guide faults found so far have been due to surface leakage due to deposits and have been eliminated by operation 2 above. With the circuit breaker closed, a power factor reading 0.005 or more in excess of the mean power factor of the 2 bushings of the same unit has been used to warrant an investigation of the lift rods and guides, provided the power factors of the 2 bushings are normal.

The actual time for testing a circuit breaker after it is prepared for test is very short. Only a few minutes are needed to take the 9 test readings for a 3-pole 3-tank breaker. The best record to date made in the field with the portable inverted Schering bridge was testing the bushings of 19 3-pole breakers and 12 potential transformers in one day without overtime. Four men were used on the test during this day. One man went ahead of the testing crew disconnecting leads, 2 men conducted the test, and the fourth man followed up the testing crew reconnecting the leads to the bushings. The number of circuit breakers that can be tested in a day depends largely upon the time taken to switch from one breaker to another, and the time required to localize a fault and remedy it.

Periodic power factor tests decrease circuit breaker maintenance as the electrical condition of the breaker is shown by the test.

TESTING TRANSFORMER BUSHINGS

The testing of a bushing on a transformer is approximately the same as for a bushing on a circuit breaker.

Table I—Results of Early Tests

Company	No. Bushings Tested	No. of Faults	No. of Bushing Faults	Other Faults (Lift Rod, Oil, Wdg., etc.)
A	376	14	10	4
B	930	45	39	6

To localize abnormal readings:

1. The exposed porcelain is shielded to eliminate surface leakage.
2. The oil end of the bushing is cleaned.

If the fault is not cleared by steps 1 and 2 above, the cause for abnormal power factor is in the bushing and it is removed from service.

On transformers it has been necessary, heretofore, to disconnect the winding from the bushing completely to make the tests, either by dropping the oil in the transformer tank and disconnecting the winding, or by attaching a rod of insulating material to the end of the lead and pushing it down and out of the central tube of the bushing. Obviously, this is a very undesirable procedure. With the inverted Schering bridge, the transformer lead requires very little insulation between it and the bushing, as the transformer lead is attached to the shielding circuit of the bridge and brought to the same potential as the bushing. In many of the transformers, the lead is taped all the way through the bushing, so that it is only necessary to disconnect it at the top of the bushing and attach it to the shielding of the testing set cable. The ground connection of the transformer must be removed during the test.

In the absence of tape on the lead, a thin-walled tube of insulating material usually can be pushed down through the bushing, surrounding the lead and insulating it from the bushing sufficiently for testing by the inverted Schering bridge method. As many as 3 transformer banks and 2 spare units have been tested in one day using the insulated lead method, while almost an entire day has been taken to test one transformer bank when the oil had to be dropped to disconnect the winding.

Potential and instrument transformers have been tested as a unit; that is, the tests are made on bushings and windings together. After a few tests are made, it is known just what one of the complete units should measure and a unit giving an abnormal reading is segregated to find the location of the fault. High loss oils, high loss winding, and high loss bush-

Table II—Typical Cases

Test No.	Kv Rating	Power Factor	Breakdown on Test	Remarks
1	44	0.046 at 23 deg C 0.097 at 50 deg C 0.27 at 80 deg C	160 kv while raising voltage to flashover	Bushing made before 1922. Trouble due to moisture entering bushing
2	66	0.077 at 20 deg C	183 kv after 58 sec	Bushing made before 1922. Trouble due to moisture entering bushing
3	132	0.075 at 20 deg C		Bushing made before 1922. Dismantled and a charred path 7 in. to 8 in. long over micarta insulation at top was found
4	66	0.0154 at 26 deg C		Capacitance was high. Oil end of bushing was found to be mechanically damaged
5	66	0.11 for complete unit 0.03 for bushing alone 0.002 for oil 0.15 for winding 0.0704 for winding after 4 days of drying at 70 deg C		Potential transformer. The high power factor of the winding was likely due to moisture. The winding was given further drying before putting into service. The bridge, however, was not available for making a test after this last drying operation
6	22	0.0626 for bushing No. 1 of unit 0.0606 for bushing No. 2 of unit 0.0666 for breaker closed 0.0856 for sample of oil 0.0205 for bushing No. 1 after cleaning oil end 0.0258 for bushing No. 2 after cleaning oil end		Circuit breaker. The abnormal power factor was due to the oil
7	66	0.0213 for No. 1 bushing 0.0186 for No. 2 bushing 0.0340 for breaker closed 0.0206 for breaker closed after lift rod and parts were cleaned		Circuit breaker. Abnormal power factor with breaker closed was due to deposits on the lift rod

ings have been found readily by this combination test. One disadvantage of the test is that the capacitance of the bushing cannot be determined.

FIELD TESTS

Tests have been made on the properties of 10 operating companies with the set in its experimental form. On some systems the tests were an investigation of bushing troubles and on other systems were a general test on all bushings. We do not have a complete record of all actual faults found in the field as 2 of the operating companies conducted their own tests.

A fair conception of what to expect from the power factor test on a power system can be had from the results given from tests on 2 power companies' systems, and summarized in Table I. These represent the first field power factor tests made with the inverted Schering bridge. The number of faults will materially decrease with repeated tests. Table II gives some typical cases and conditions of bushings found by the tests.

The decrease in dielectric strength occurring with increasing of power factor is shown in Fig. 6.

A bushing operating on a line having a rated circuit voltage lower than the bushing normal voltage class may safely be left in service with a power factor higher than a bushing operating on a line at its normal voltage, and still be satisfactory.

CONCLUSION

The tests show that the power factor device actually does show deteriorated apparatus, provided the design of the equipment is known. A satisfactory device has been developed which will do the work quickly and with relatively little trouble. The use of the device, in coöperation with the manufacturer of the apparatus, will provide the user with experience in the location of insulation troubles and permit the user to detect defective equipment in time to prevent outages, and thus reduce operating expenses.

Pantograph Trolleys
I—Design Features

Improvements have been made in practically every part of pantograph trolleys used for current collection on electric railways. As a result of these many improvements the pantograph of most recent design fulfills its important function in a highly satisfactory manner. Designs now are available for collecting currents of any magnitude found on either a-c or d-c roads at any speed up to 100 mph.

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A SUPERFICIAL examination of a pantograph trolley would indicate that there had been very little change in design. As a matter of fact, however, there have been important changes involving practically every part of the pantograph. Serious troubles were experienced with original insulation. Improvements in insulation have been made so that insulator troubles are now unheard of. Operation was very sluggish, and pressure was very irregular. By use of tension springs, self-aligning bearings, and change in bearing location, friction has been almost eliminated, and almost uniform pressure has been obtained throughout the operating range.

Original pantographs had only small current collecting capacity. At present there are designs for collecting currents of any magnitude at any speed up to 100 mph, on either a-c or d-c systems. The range of operation has been increased to be suitable for 24-ft 6-in. operating height, and 15-ft 3-in. minimum operating height. In addition to original designs which were (1) spring-raised air-lowered, (2) air-raised gravity-lowered, and (3) air-raised spring-lowered, types have been developed that have elements of safety not found in original designs. The original designs of air raised pantographs also have been improved to give lower maintenance and greater safety.

Structural improvements have been made to give greater stability and a simpler structure. Parts have been standardized to reduce the number of types of component parts to a minimum. As a result of these many improvements, the pantograph collector of most recent design fulfills its important function in a highly satisfactory manner.

GENERAL

Pantograph trolleys were first developed in the United States in 1906, at which time the New York,

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New Haven, and Hartford electrification necessitated the use of this type of current collector. Various problems have been encountered in pantograph current collection; and although the general form of construction has not changed greatly from the original New Haven pantographs, the improvements which will be discussed were required to obtain higher operating speeds, greater collection capacity, uniformity of contact pressure, freedom from sluggishness, and more positive operation. While the improvements that have been made up to the present time are taking care of present conditions, further improvements must be made for speeds in excess of 100 mph. Experience indicates that these conditions can be met without great difficulty.

As the roller type of pantograph has proved to be inadequate and has been replaced with a sliding shoe, this paper will be confined to the latter type. The component parts of a modern pantograph collector are:

1. The collector shoe.
2. The movable framework consisting of an upper and lower member.
3. The cross shaft which supports the movable frame.
4. The pantograph base which carries the cross shaft bearings, operating air cylinders, main springs, jack shafts, and automatic latch.
5. The pantograph insulators to which the base is connected and which insulate the pantograph from the roof of the car or locomotive.

The simplest form is the hand operated pantograph in which the contact pressure is supplied by either tension, compression, or torsion springs. Lowering is accomplished by means of a rope passing over a series of pulleys. This lowering rope may have the end held positively in the down position, or the pantograph may be held down by a latch which is released by a rope. Hand operated pantographs are little used because of the greater ease with which the air operated pantographs are controlled.

AIR OPERATED PANTOGRAPHS

Air operated pantographs can be divided into the following 3 types:

1. Spring-raised air-lowered with automatic latch.
2. Air-raised gravity-lowered: (a) held in collapsed position by gravity only; (b) held in collapsed position by gravity and an automatic latch.
3. Air-raised spring-lowered without latch.

In the first design the pantograph is raised by springs. It is lowered by means of air pistons acting on levers that counteract the moment of the raising springs and return the pantograph to the latched height. At this point an automatic latch engages the frame and holds the pantograph in the latched position. To release the pantograph, air is admitted to the latch cylinder. This releases the latch and permits the pantograph to rise.

The raising and pressure mechanism consists of cams, cam chains, and tension springs (see Fig. 1); the lowering mechanism consists of push levers, air cylinders, and pistons (see Fig. 2).

Raising and Pressure Mechanism. Although fair results have been obtained by means of springs, connecting rods, and levers, it is impossible to locate the lever and connecting rods so that the moments obtained throughout the angular movement correspond closely with the combined moments of lower frame, upper frame, contact shoe, and required contact pressure. A tension spring is the simplest and most direct means of applying pressure. Tension adjustments are made very easily to vary the contact pressure of the pantograph shoe. The raising moment is imparted to the main shaft by tension springs connected to a cam by means of chains. The shape of the cam is such that the variable moments throughout the operating range are counteracted and sufficient pressure moment added so that approximately uniform pressure is obtained throughout the operating range. The flexible connection from operating springs to the cam may be a flexible band, cable, or chain. Of these means a flat link chain has been found most suitable, due to strength and facility of making the end connections to the cam and spring.

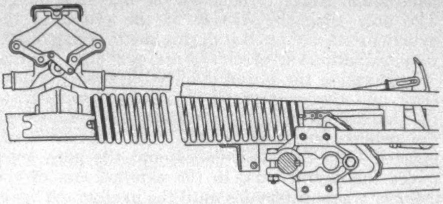
Fig. 1. Spring, cam, and chain

Lowering Mechanism. The lowering mechanism, Fig. 2, consists of a push lever keyed to the shaft, and air cylinders and pistons for exerting pressure against the push levers to produce a counter moment for lowering the pantograph. The push lever is provided with a roller at the point of contact with the piston to avoid the sliding resistance that otherwise would result at the end of the push lever. The lowering piston is provided with a suitable air packing at one end, and a loose sliding fit in the

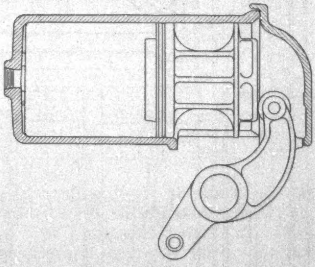
Fig. 2. Air cylinder and push lever

cylinder at the other end to guide the piston in the cylinder and to prevent tilting. With this construction when the pantograph has attained its maximum height, the piston remains at the extreme end of the cylinder, and the push lever moves freely throughout its range of angular movement with no friction due to the piston during movements of the pantograph frame throughout the operating range. The only time the friction of the piston in the cylinder is encountered is during the lowering operation by admission of air to the cylinder. During this operation the piston is forced against the push lever and the pantograph is brought promptly to the latched position. In raising the pantograph the reverse operation results when the air is exhausted from the air cylinder, and the push lever forces the piston back to the extreme end of the cylinder where it remains until the pantograph again is lowered.

RETARDATION OF PANTOGRAPH MOVEMENTS

It is essential that simple means be provided against the pantograph being lowered too rapidly when air is admitted to the cylinders, and against raising too rapidly when the air is exhausted. This is accomplished very simply by a diaphragm in a pipe union between the air cylinder and equipment air piping. This diaphragm has a small hole in it which serves to check the admission of air to the cylinder and permits lowering in $1^1/_2$ to 2 sec to the latched position. This same diaphragm prevents too rapid raising by retarding the speed with which the air is exhausted from the cylinder. There will be a decided retardation in ascent even though the air in the main cylinders has only atmospheric pressure, as some compression will result when the piston moves forward. It is desirable, however, to admit air to the main cylinders before admitting air to the latch cylinder, so that there may be the added retardation in raising due to air under pressure being exhausted from the main cylinders.

In the second design (2a) the pantograph is raised by the admission of air to the main cylinders, which act through the springs, etc. In order to reduce the size of the main cylinders and also to aid

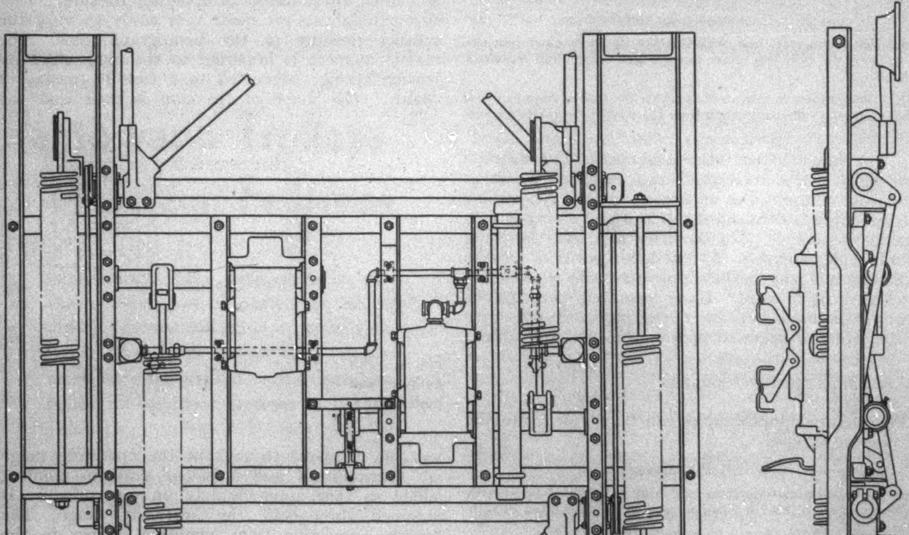

Fig. 3. Air raised pantograph with compressed air buffer and automatic latch

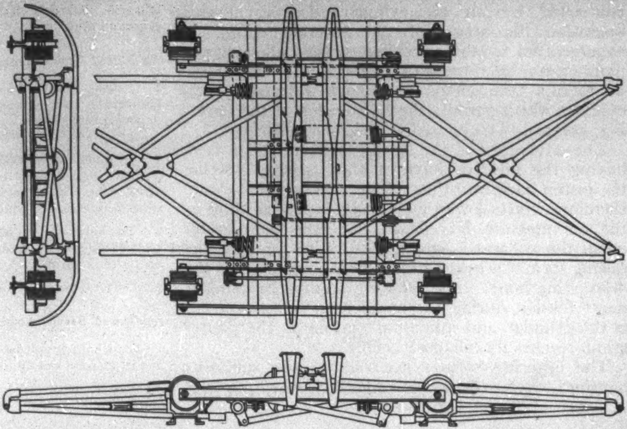

Fig. 5 (right). Air-raised spring-lowered pantograph

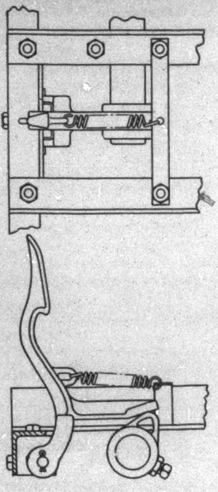

Fig. 4 (below). Latch and mechanical release

in retarding the lowering of the pantograph when the air is exhausted, 2 sets of springs are used: One set is for approximately balancing the dead weight of the pantograph; the other set may be called the pressure springs. Tension in these springs is supplied by means of air cylinders and pistons. When these springs are placed under tension, the pantograph begins to rise. When the piston is at the end of its stroke, full tension has been supplied to the pressure springs, and this condition is maintained as long as the pantograph is in operation. To lower the pantograph, the air is exhausted from the main cylinders and the pantograph comes to rest at the collapsed height. A careful predetermined relation must exist between the balancing and raising springs. If these springs are too evenly balanced, there is a decided slam when the pantograph reaches the buffers. The raising springs, therefore, should have sufficient tension in the collapsed height so that a force of 30 lb is required at the pantograph shoe to raise the pantograph. Owing to the low collapsed height at which a majority of pantographs are required to operate because of low minimum height of contact wire, a satisfactory simple type of buffer is difficult to design. About the only alternative is a compressed air buffer, as shown in Fig. 3.

This compressed air buffer consists of a small vertical air cylinder at either side of the pantograph. This cylinder is provided with a piston having a buffer that permits an air cushioned movement of about 2 in. Normally during operation of the pantograph this buffer is in an extended position due to air pressure exerted on the piston. When the air is exhausted from the main cylinders, the air also is permitted to flow from the buffer cylinders, but is retarded by means of an auxiliary air reservoir and a diaphragm in the air connection with only a $^1/_{32}$-in. hole permitting the air to flow from the auxiliary reservoir and buffer cylinders very slowly; thus there is still considerable pressure in the buffer cylinder when the pantograph frame comes into contact with the buffer. Without the auxiliary reservoir the air would be exhausted too rapidly from the buffer cylinder, and not much cushion effect would be obtained.

In design 2b a holding-down automatic latch, Fig. 4, has been added to the air raised design. This becomes necessary in some cases where for long distances the pantograph operates on a contact wire very close to the collapsed height of the shoe. As the movable parts are more or less balanced, and are held down only by gravity, there is some tendency for bouncing of the pantograph, so that the contact shoe may raise some distance above its collapsed height. This automatic latch holds the pantograph positively in the collapsed position and is applied as a safety measure under low wire. The latch is released when air is applied for raising the pantograph, by a cam on a jack shaft. See Figs. 3 and 4. This design is now in successful operation on the Cleveland (Ohio) Union Terminals Railway.

AIR-RAISED SPRING-LOWERED PANTOGRAPH

In this design, Fig. 5, the contact pressure is supplied by tension springs. These pressure springs are opposed by lowering springs which have sufficient strength to overpower the pressure springs and lower the pantograph. The lowering springs are controlled by an air cylinder. During normal operation the action of the lowering springs is counteracted by the air cylinder, thus allowing the pantograph to raise and operate. To lower the pantograph the air is exhausted from the main cylinder which permits the full tension of the lowering springs to be opposed to the raising springs.

The advantage of the spring lowered design is in having the positive force of these springs forcing the piston back into the cylinder. The pantograph, therefore, starts lowering very promptly as soon as the air pressure is released. As the pantograph nears the collapsed height, the entire force of the raising springs is exerted to cushion the inertia of the descending mass. The lowering springs have maximum tension during the application of air pressure in the cylinder, and minimum tension as the pantograph reaches its collapsed height.

The lowering springs need have only sufficient tension to overbalance somewhat the pressure moment of the raising springs plus the friction of the piston in the air cylinder, and the resistance of compressed air being forced from the cylinder. The air cylinder need have only sufficient capacity to overcome the full tension of the lowering springs plus the air piston friction.

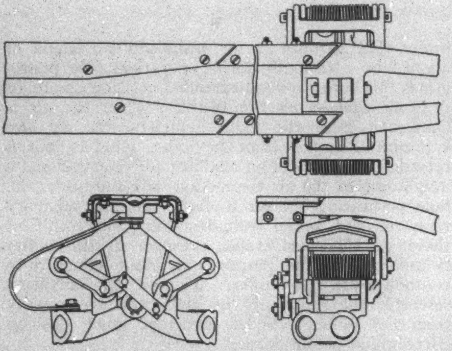

Fig. 6. Single contact shoe and accessories

Relative Advantages of Different Designs

Spring-Raised Air-Lowered Type

1. In case air pressure is not available, it is only necessary in most modern types to trip the automatic latch by means of a wooden pole with hook attachment, and a lever arm connected with the mechanical release mechanism which is at the side of the pantograph. This can be reached easily from the ground with the hook pole. See Fig. 10.

2. In lowering the pantograph, as soon as air pressure is supplied to the lowering cylinders the pantograph begins to lower and continues lowering rapidly until the latched height is reached.

3. In case of an air leakage so that there is a gradual reduction in air pressure, the pantograph is not affected when the shoe is in contact with the line.

4. In case the air cylinder packing may have slight leakage, this will take place only during the lowering operation, when leakage is not important.

Air-Raised Gravity-Lowered Design 2a

1. Pantograph is held in collapsed position by gravity only. The pantograph may be raised somewhat above the collapsed height by bouncing or by wind currents, but is secure against overraising to operating height except by application of air pressure.

2. In low collapsed height where action is rather sluggish, the design lends itself easily to the application of a compressed air buffer, which also has the valuable feature of making the pantograph rise promptly when air pressure is applied.

3. The balancing springs are practically without tension while the pantograph is in collapsed position. This will result in much longer life for these springs.

4. Only 1 air connection to insulate in place of 2.

Air-Raised Gravity-Lowered Design 2b

1. This pantograph has advantages Nos. 2, 3, and 4, of design 2a and in addition has a positive latch.

Air-Raised Spring-Lowered Type

1. This design has all the advantages of the air-raised gravity-lowered type, and in addition can be raised or lowered as promptly and uniformly as the spring-raised air-lowered type.

2. Less cylinder capacity is required than for the air-raised gravity-lowered design.

Relative Disadvantages of Different Designs

Spring-Raised Air-Lowered Type

1. This type is held in the collapsed position by means of an automatic latch. Should this latch not latch properly or shake loose, the pantograph will rise immediately.

2. In case of failure of the air supply, the pantograph would remain in contact with the line. In some cases this might be undesirable, as it might be safer and better to delay operation until the air supply is reëstablished.

Air-Raised Gravity-Lowered Type 2a

1. Difficulty in raising the pantograph without an air supply.

2. Excessive air leakage which may result because of air being applied continuously while the pantograph is in contact with the line.

3. Less speed and uniformity in raising and lowering.

4. Pantograph is not held positively in the collapsed position, and may be subject to bouncing which is objectionable on long stretches of low wire.

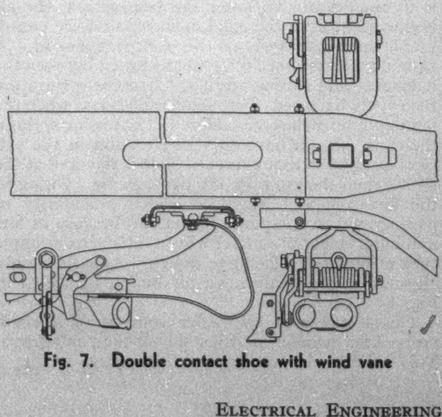

Fig. 7. Double contact shoe with wind vane

Air-Raised Gravity-Lowered Type 2b

1. Same disadvantages as type 2a, but is held positively in the collapsed position by an automatic latch.

Air-Raised Spring-Lowered Type

1. Pantograph is difficult to raise without an air supply.
2. Excessive air leakage may result because of the air being supplied continuously while the pantograph is in contact with the line.

COMPONENT PARTS OF THE PANTOGRAPH

Contact Shoe. In the development of the pantograph shoe it has been found that a length of contact surface of 48 in. is sufficient for the majority of overhead construction now in operation. A length of 72 in. is found sufficient for the length over end horns. In the Virginian Railway electrification this distance was increased to 84 in. In this case it was believed that economy could be effected by using longer spacing of the overhead supporting structures resulting in greater displacement of the contact wire from the center of the track. This requires a longer shoe. Shorter shoes also are in successful operation. The Southern Pacific and Key System use a shoe with a contact surface 36 in. long, and with a length over end horns of 72 in. In each of these cases the short length of shoe is due to the overhead structures being built so that the contact wire is nearer the center of the track than elsewhere. The Chicago, Milwaukee, St. Paul and Pacific Railroad uses a shoe with a contact surface only 34 in. long, and with an over-all length over end horns of 84 in. This short length was necessitated by tunnel conditions, and as the overhead construction was designed for a shoe of this length, satisfactory operation is obtained. The shape of the end horns is determined in several cases by low overhead clearances to which the end horn must conform.

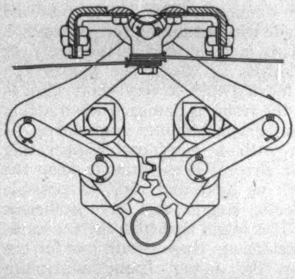

Fig. 8. Southern Pacific Railroad contact shoe

Various materials have been tried for contact shoes. The aluminum bow which was used at first had a very short life. This was followed by a shoe having a wood base with a combination of aluminum and copper contact strips, and with a shoe made of sheet copper. This sheet copper shoe was followed by a sheet steel shoe, which still is used by important roads such as New York, New Haven & Hartford, Pennsylvania, Canadian National Sarnia Tunnel electrification, and Boston and Maine. These are all single-phase a-c systems. The standard construction generally adopted consists of a shoe with copper-bronze or steel wearing strips. This construction is shown in Fig. 6. In this design the shoe is an inverted trough section $4^1/_2$ in. wide, made of sheet steel or aluminum alloy $^1/_{16}$ in. thick. There are 2 long center wearing strips 24 in. long and 4 end strips 12 in. long. The center strips are 2 in. wide in the center and taper near the ends. Each of these strips is held with 4 flat-head bronze screws. This construction has been adapted to leave a clear central space of about 12 in. free from screw heads, as most of the wear occurs in that space. These strips have an outer edge with a $^3/_8$-in. radius to give an easy approach on the contact wire, and one that is less likely to catch onto projecting clamps.

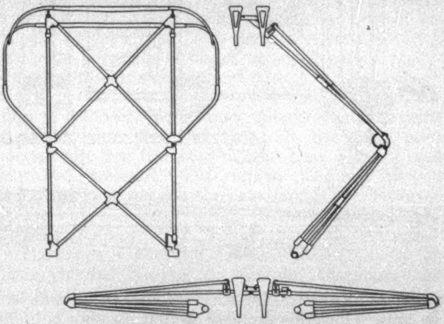

Fig. 9. Pantograph with side guards

A rather unique contact strip is used by the Southern Pacific and by the Key System. This is shown in a cross section of the shoe, Fig. 8. The outside strips are of bronze angle stock $1^1/_4$ x $1^1/_4$ x $^3/_{16}$ in. The inside strips are half oval 1 x $^7/_{32}$-in. open-hearth steel. A copper contact wire is used. The space between strips is filled with a grease and graphite compound. A nicely polished contact wire has resulted, and very little wear can be observed. The action of the steel and bronze combination is not understood exactly, but it is probable that any rough spots appearing on the contact wire are removed quickly by the action of the steel strips.

In a majority of single-phase 11,000-volt electrifications a single shoe has been found to satisfy operating conditions. For nearly all d-c electrifications, and some heavy traction a-c electrifications, a double shoe (Fig. 7) is found essential. With 2 shoes having independent flexibility and supported so that the shoes are about 12 in. apart center to center, almost sparkless collection will result with a flexibly supported catenary system, collecting current of 1,000 amp at 60 mph, and 2,500 amp when starting. For high speed operation at 50 to 75 mph, the wind

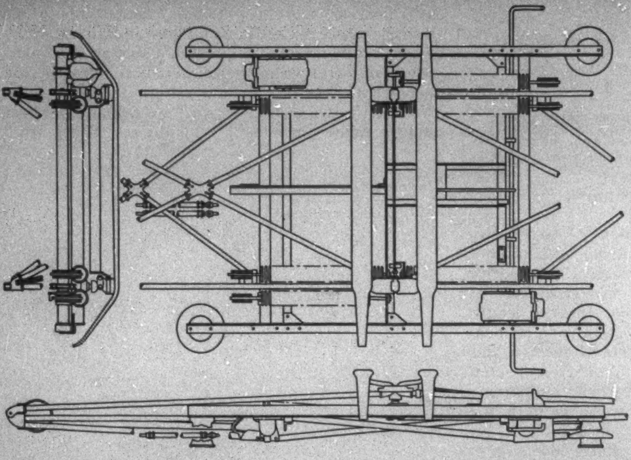

Fig. 10. Spring-raised air-lowered pantograph

pressure on the trailing shoe is found to be sufficient to cause a lowering moment so that the shoe actually will leave the wire. To correct this condition a wind vane is applied as shown in Fig. 7. This wind vane is located in the center of the pantograph, and is suspended at a sufficient distance below the shoes so that the wind pressure acting on it will produce a counter moment to that exerted on the trailing shoe; as a result, the shoe is held in contact with the line. It was found also that the shoe supporting arms must have a length of $7^{1}/_{2}$ in., thereby increasing the ratio of contact pressure moment to wind pressure moment. Without the wind vane an excessive length of arm would be necessary.

It is extremely desirable to have independent flexibility for the contact shoe. Owing to low minimum operating height and collapsed height, it is a difficult matter to obtain a suitable flexible shoe. In the double-shoe design a 2-in. range of movement is obtained with the design shown in Fig. 7. A 2-in. range also is obtained in the single-shoe design shown in Fig. 6.

Lubrication of the pantograph shoe is essential; without it excessive wear will occur on both the wearing strips and the contact wire. The space between contact strips provides a recess for the lubricant. A mixture of 1 part flake graphite and 2 parts motor grease has been used with good success.

In order to have a smooth passage of the contact shoe at sidings and crossings, the shoe is provided with end horns having a shape depending on overhead clearances in tunnels. In the first designs these end horns had a drop of 8 in. This has been increased in later designs to 12 in., to reduce the tendency for the contact wire to pass under the horn when the line is slack. In order positively to prevent the wire from being caught under the end horn, designs have been developed in which side guards have been added to the upper pantograph frame. This is shown in Fig. 9. These side guards are made of aluminum alloy tubing, and are clamped to a standard pantograph frame. Should the guards become damaged, they can be removed until repairs are made without taking the pantograph out of service. This is a decided advantage over some European designs in which the pantograph frame itself is so formed that a very short horn is required. In case the frame is damaged when acting as a guard, the pantograph becomes inoperative.

In pantographs with a considerable operating range and a double shoe, it is essential to keep the movable framework as light and rigid as possible to carry the collector weight and give sufficient contact pressure. It is found that high carbon seamless steel tubing best meets these conditions for the lower frame. For the upper frame maximum strength and minimum inertia are obtained with aluminum alloy tubing. It is essential that both upper and lower frames be cross-braced adequately, and that the frame connecting castings be machined carefully to eliminate loose connections. All the pin holes should have hardened renewable bushings, and all pins should be case hardened or heat treated to reduce wear of these parts.

Even though the upper and lower frames have excellent lateral rigidity, a decided side sway of the pantograph may result because of the torsion of the main shaft. When a lateral force is applied to the pantograph, this force causes a moment about the pantograph base. The upper frame is supported by the lower frame, and this moment of the upper frame including shoes is resisted by the lower frame; thus a twisting moment is applied to the shaft at one side of the pantograph, which is opposed to the twisting moment at the opposite side. Any twisting of the shaft is multiplied greatly at the end of the lower frame, and results in a rocking or side sway of the pantograph. It is essential, therefore, that for high speed operation the pantograph shafts have great torsional rigidity. A hollow shaft of large diameter meets this requirement. It is essential also that there be no lost motion between the lower frame and the main shaft. In older designs solid cross-shafts and keyed frame connections were used. In a recent modern design the connection of the lower frame to the main shaft consists of steel plates welded to the shaft. The lower frame tubing is flattened and fastened to these shaft plates by 4 $^3/_8$-in. ream bolts in double shear.

Pantograph Bearings. In older designs not much attention was paid to the main bearings. The general arrangement was such that in some designs 8 bearings were used. In modern designs only 4 bearings are used, and these are self-aligning roller bearings. This results in a very free response of the pantograph frame, and friction amounting to only $1^1/_2$ to 2 lb measured at the shoe throughout the pantograph operating range. Figure 11 shows a roller bearing in which the bearing itself is self-aligning. The bearing support has an end play arrangement which permits longitudinal adjustment. Both types of bearing are provided with "alemite" fittings for lubrication, and felt washers to exclude dust.

Pressure Adjustment. In order to have a good range of pressure adjustment, an adjustable cam has been developed; this is shown in Fig. 12. By means of the set screw shown, a decided increase or decrease in pressure can be obtained at the lower or upper part of the operating range.

Latching Arrangement. The most satisfactory location for the latch is found to be near the center of the pantograph, both transversely and longitudinally. A great many designs have the latch engage the cross casting on the upper frame. For a long range pantograph with aluminum alloy tubing, the latch at this point causes considerable sag of the upper frame, and does not permit such a low latched height as where the latch is located near the center. The shape of this latch is such that the pantograph frame will engage the latch when lowered from a height 3 in. above the latch height of shoe.

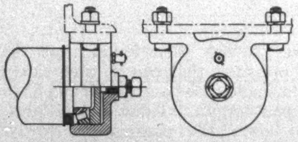

Fig. 11. Self-aligning roller bearing

Frame Details. Although a rather minor detail, the hinge connection between upper and lower frame has an important bearing on a freely operating pantograph without excessive side play. In a late design, Fig. 12, this connection is provided with a hardened bushing and hardened hollow pin with "alemite" fitting to provide for good lubrication. To reduce wear in the joint, brass washers are inserted in the hinge.

Base Frame. In order to simplify the pantograph base, the latest high speed design has an angle-iron base with only a single angle on each side, and 3 transverse angles. Gusset plates are provided to make a rigid frame. The side angles are adapted for resting on top of pillar type insulators. Figure 10 shows the angle iron base as a part of a complete pantograph.

Insulators. Marked improvement has been made in pantograph insulation. The insulation of the pantograph from the roof of the car or locomotive requires 4 insulators. These may be of either spool or pin types. The spool type of insulator is satisfactory for voltages up to 1,500 volts. For voltages over 1,500 up to 3,000 volts, a petticoat type of insulator is desirable. This insulator consists of a one-piece porcelain insulator provided with a malleable iron shield, adapter, and base.

For 11,000 volts a pin type insulator is required. This is a 2-piece porcelain insulator provided with malleable iron cap and base. It has been used successfully by the New York, New Haven, and Hartford Railroad. This design does not have a metal shield protecting the porcelain. The flashover voltage of the latter design is only about 60,000 volts as compared with 80,000 volts without shield.

The insulator with shield is used successfully by the Pennsylvania, Norfolk & Western, Virginian, and the Reading roads in 11,000-volt operation, but in addition to the primary set of insulators on the pantograph, there is a set of secondary insulators applied to an insulated base so that double insulation is obtained.

A one-piece porcelain pillar type of insulator is especially well adapted for 11,000-volt pantograph insulation by using 2 sets of insulators. The pantograph shown in Fig. 10 rests on 4 primary insulators. These primary insulators rest on an insulated base which rests on the secondary insulators. Failure of either a primary or secondary insulator will not delay operation, as either insulator has sufficient capacity to provide insulation for a long period. This design is now in use on the Pennsylvania Railroad passenger locomotives.

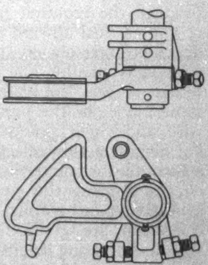

Fig. 12. Adjustable cam

An insulated air connection also is required. This insulation is supplied by a rubber hose. Recently a porcelain tube insulator has been developed which gives promise of supplanting the rubber hose and thus decreasing maintenance cost. The end connections have rubber packing which gives a certain amount of flexibility and thereby avoids fracture of the porcelain tube.

Pantograph Trolleys
II—Operating Features

Satisfactory current collection on electric railways using pantograph trolleys depends on the ability of the pantograph to follow irregularities in the height of the contact wire at all operating speeds and within a limited range of pressures between the contact wire and the shoe. In this paper operating characteristics of pantograph collectors are outlined, and operating data for 3 typical pantographs are given.

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SATISFACTORY current collection by electric cars and locomotives using pantograph collectors depends on the maintaining of a constant pressure by the collector on the contact wires. This pressure is limited to a very small range. At high speeds of operation the collector must accelerate rapidly to follow variations in the height of the contact wires. If all the available spring force is used accelerating the pantograph there is none left to produce the required pressure against the wires.

The vertical upward acceleration of a pantograph depends inversely on its inertia and friction. The friction is small. The inertia may be expressed in terms of an "equivalent weight" which has the same inertia as the pantograph itself at the contact wire, and which consequently varies with the operating height of the collector. In this paper are given a formula for computing the equivalent weight, and curves showing the equivalent weights of 3 representative pantographs. The possible rates of acceleration are given for these 3 pantographs at various operating heights.

Curves are given for one of the pantographs showing its upward rise for certain time intervals, and for horizontal travel when operating at various speeds. These curves show the limits of the pantograph's ability to follow the wire at high speeds, which limits should be taken into account when designing overhead contact systems for high speed operation. For speeds of 100 mph or more both pantographs and contact systems will have to be improved for satisfactory current collection.

Pantograph Pressures

The ability of a pantograph to maintain pressure against the contact wires of the overhead catenary system on which it operates, at high speeds of operation, with variations in the space between the car or locomotive roof on which it is mounted and the contact wires, depends directly on the pressure it can exert against the contact wires and inversely on the friction and the inertia of the moving parts. The pressure is limited by 2 main considerations: danger of entanglements with the wires of the overhead system, and danger of excessive wear on the contact wires. In general the lighter the contact system, the lower must be the pantograph pressure for safe operation. It has been found that the maximum normal pressures that can be used safely are about 18 lb for a single-shoe pantograph and 35 lb for a double-shoe pantograph. These are the pressures required to lower the pantograph slowly. Since the pantograph pressure is limited by the contact system on which it will operate, the only way of improving the operating characteristics is by reducing the friction and the inertia of the moving parts.

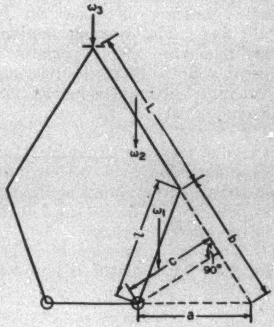

Fig. 1. Line diagram of pantograph

On modern pantographs for high speed operation where roller main bearings are used, friction has been reduced to 5 or 6 per cent of the total pressure in the case of double-shoe pantographs. There is some possibility of reducing this still more, but the reduction would be small and so far has not been found necessary. Friction adds to the force necessary to lower a pantograph and reduces the pressure against the contact wires when the pantograph is rising.

The inertia of a pantograph depends on the weight and arrangement of its moving parts, and also varies with the position of the pantograph. The several moving parts have varying influence on it: The shoe, which is directly in contact with the overhead system and which must follow all variations in the height of the contact wires to remain in contact with them, has the most. The upper frame, which supports the shoe at its apex, does not have to move its entire mass quite as fast as the shoe,

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particularly in the lower range of operation, and thus has less influence on the inertia. The lower frame has still less.

It is possible to determine an equivalent weight for any position of the pantograph, which, if placed at the contact wire, would have the same inertia as the pantograph itself. This equivalent weight can be used to calculate the acceleration, or the force at the apex of the pantograph necessary to accelerate the pantograph, in a vertical direction. The ability of a pantograph to follow the contact wire at high operating speeds depends inversely on this equivalent weight. It varies with the height of the pantograph, increasing rapidly as the maximum height is approached. The formula for determining the equivalent weight is obtained by assuming that a force acts on the apex of a pantograph through a small distance; from an energy equation the velocity of the apex is found, taking into account the energy of each moving part due to the linear motion of its center of gravity and its energy due to rotation; then a weight is found which if acted on by this same force through the same distance would obtain the same velocity. This weight is the equivalent weight. The formula is

$$W_e = w_3 + w_2 \frac{(12\,c^2 + b^2)}{6\,a^2} + w_1 \frac{(2\,l^2)}{3\,a^2}$$

where

W_e = the equivalent weight

w_3 = weight of shoe (or shoes) and supporting mechanism

w_2 = weight of one-half upper frame

w_1 = weight of one-half lower frame

l = length of the lower frame

a, b, and c are as shown in Fig. 1

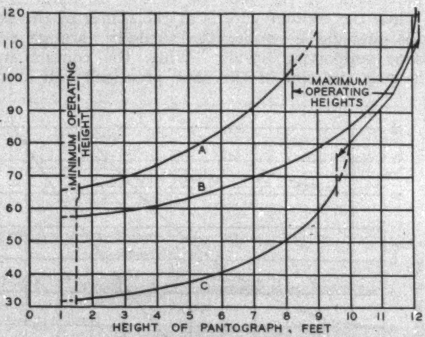

Fig. 2. Equivalent weights of pantographs A, B, and C

A high contact wire is desirable from the standpoint of safety to trainmen, but it makes the problem of designing a pantograph for high speed operation more difficult. A high contact wire requires a long range pantograph operated near its upper limit, as there is no extensive electrification without low bridges or tunnels which set the lower limit of operation. The pantograph also must have a low collapsed height, as there is usually little space between the top of the locomotive or car and the minimum height of the contact wire. A pantograph does not accelerate as rapidly near its upper limit as can be seen from the equivalent weight and acceleration curves given later. It is also difficult to maintain the full pressure near the maximum height of operation.

Table I—Data for 3 Typical Pantographs (See Fig. 1)

Pantograph	Total Weight, Pounds	No. of Shoes	Operating Range, Inches	Inches		Pounds		
				l	L	w_1	w_2	w_3
A	840	2	79.5	54	$71\,^3/_8$	37	25	59
B	1,135	2	129	66	99	42	22	50
C	620	1	97	54	76	25	15	27

Some data on 3 typical pantographs which will be studied are given in Table I. Figure 2 gives the equivalent weights of these 3 pantographs calculated by the preceding formula. The heights are given above the center of the main shafts, and the maximum and minimum operating heights are indicated.

From these equivalent weights and the pantograph pressure the free vertical acceleration of the pantograph can be calculated starting from any given operating height. The free acceleration is obtained when all of the available spring force is used to accelerate the pantograph upward, with no resistance except the inertia of the pantograph itself. The equivalent weight also can be used to calculate the added force necessary to lower the pantograph at given rates of acceleration.

When there is any slope to the overhead wires which forces the pantograph downward, the pressure on the contact wires is increased by the amount of force necessary to accelerate the pantograph. When the slope permits an upward movement the pressure on the contact wires is reduced by the amount necessary to accelerate the pantograph upward. At slow operating speeds these variations are not great; but as the speed of the car or

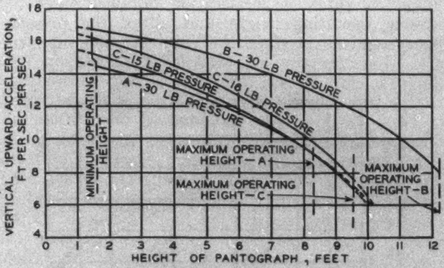

Fig. 3. Pantograph accelerations vs. pantograph height

locomotive is increased, a large part of the pantograph pressure may be used accelerating the moving parts, or the pressure on the contact system may be increased to a point where excessive wear occurs. Where the pressure is decreased, it may become so low that arcing occurs which also will cause excessive deterioration of the contact wire. There is a certain limited range of pressure where the maximum life of the pantograph wearing strips and contact wire is obtained. For pressures lower than this the wear increases, and for higher pressures the wear also increases.

The curves in Fig. 3 have been drawn to show how the 3 pantographs being studied will accelerate at various operating heights. These curves are based upon the assumption that all of the available pressure is used to accelerate the pantographs. In Fig. 4 the curves have been changed to show the possible acceleration at any given percentage of the maximum operating height. The flatness of the curve for pantograph *A* is due to its short operating range compared with the other 2 pantographs. Oscillograph tests made several years ago on pantograph *A* indicate that the actual curve is even flatter than the calculated one. The calculated values check the test values very closely near the upper part of the operating range, but in the lower part the test values are somewhat less than the calculated values.

In Fig. 5 curves have been plotted showing the rise of pantograph *B* (in feet) for time intervals from 0 to 1.4 sec for 3 different operating heights. They show the rate of rise starting from these heights with all available pressure being utilized to produce the rise. The normal operating height with a 24-ft contact wire has been indicated on the curves.

In Fig. 6 the vertical rise of pantograph *B* in inches is plotted against its horizontal movement in feet for various speeds of travel. These curves are based upon the rates of acceleration obtained near the normal operating height and all of the pressure being used to produce the rise. At 100 mph the pantograph can rise 1 in. in 15 ft, 3 in. in 29 ft, and 12 in. in 62 ft of horizontal travel. If the pantograph is being forced down, the pressure between the shoe and the contact wires will be doubled if forced down at these rates.

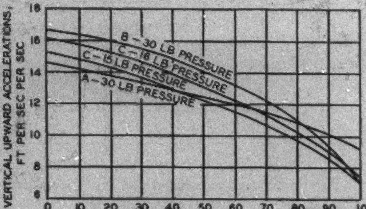

Fig. 4. Pantograph accelerations vs. per cent operating range

In order to follow the contact wire better and to reduce excessive pressures which might be caused by small grades in the contact system, auxiliary springs are introduced between the pantograph shoe and the supporting frames. This reduces the mass making small movements and tends to keep the pressure of the shoe against the wire more nearly constant. In the case of pantograph *B* each shoe weighs 16 lb. The force necessary to accelerate these shoes through 1 in. in 0.1 sec (the time for the pantograph to travel 15 ft at 100 mph) is only 5 lb per shoe or 10 lb for the 2 shoes, while 31 lb would be required if the entire frame moved the same distance in the same time. Pantograph *B* has a pressure of 31 lb going up and 35 lb coming down throughout most of its operating range; the friction is 2 lb. If there is a rise of 1 in. in the contact system and the springs are effective, the pressure on the contact wires would be 21 lb for a speed of 100 mph; if there was a fall of 1 in. the pressure on the contact wires would be 45 lb.

In this connection it should be noted that these auxiliary springs are not always effective. Each end of the shoe is supported independently and the movement of the shoe is limited to about 2 in. When the contact wire is at the center of the shoe the pressure is transmitted equally through each shoe supporting spring. When the contact wire is near the end of the shoe practically all of the pressure is transmitted through one spring. If the shoe springs are adjusted so that they come into play with the contact wire at the center of the shoe, then they will be solid and ineffective in cushioning downward movements when the wire is at one end of the shoe. If a stiffer spring be used it will not be useful in following rises in the contact wire with the wire at the center of the shoe, but will follow rises with the wire at the end of the shoe and will act as a cushion where the slope of the contact system is downward.

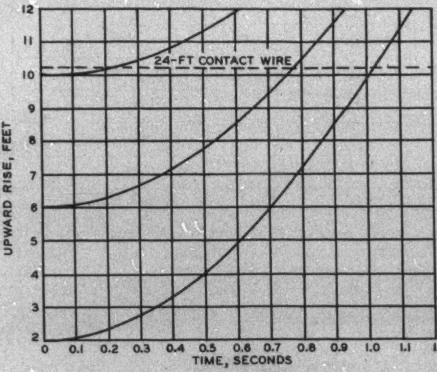

Fig. 5. Rate of rise of pantograph B

Where high operating speeds are to be used, it is necessary to depend on the contact system for a flexible path that will not require too rapid accelerations of the pantograph shoe; great care must be used in designing the contact system, and a pantograph designed especially for high speed operation should be used. Particular care must be used in designing the contact system at approaches and exits from low bridges and tunnels where changes in grade are large, and where clearances require a fairly rigid construction under the bridge or tunnel changing to the more flexible regular construction outside.

The normal catenary construction should be made as flexible as possible at the support so as not to require such a rapid change in direction that the pantograph might not be able to follow the contact wire. In the span the pressure of the pantograph reduces the load on the messenger causing it to lift the contact wire. The rise is maximum at the center of the span. At the support the pantograph pressure lifts the wire very little so that as the pantograph moves from span to span it rises and falls in each span.

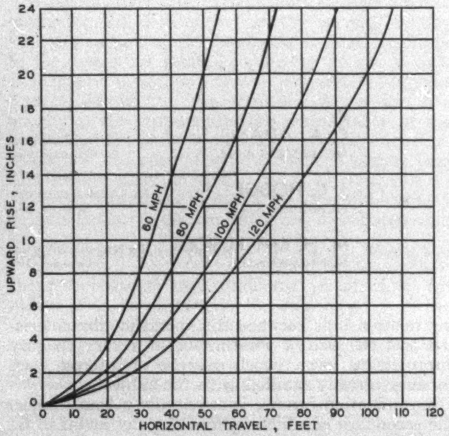

Fig. 6. Upward path of pantograph B vs. horizontal travel

Suppose the pantograph has a horizontal speed of 150 ft per second (approximately 100 mph) and that it is moving along a section of track having 300-ft spans that permit the pantograph to rise 1 ft higher in the center of the span than at the support (see Fig. 7). In 1 sec the pantograph will rise 1 ft; in the next it will be forced down 1 ft. If the acceleration up and down is constant, the average vertical velocity will be 1 ft per second and the maximum 2 ft per second. The maximum velocity will occur at the quarter points in the span. If the acceleration gives a velocity of 2 ft per second in the time it takes the pantograph to travel over a quarter of the span ($^1/_2$ sec) then the rate of acceleration is 4 ft per second per second. The acceleration and velocity are both upward in the first quarter of the span. The velocity changes from zero at the support to the maximum of 2 ft per second at the end of the quarter span. In the second quarter of the span the velocity is still upward, but the acceleration is downward which changes the velocity to zero at the center of the span. In the third quarter the acceleration and the velocity are both downward with the velocity reaching a maximum at the end of the quarter. In the fourth quarter the acceleration changes to upward while the velocity continues downward and reaches zero at the end of the span. Pantograph *B* with a pressure of 31 lb going up has an acceleration of approximately 10 ft per second per second. An acceleration of 4 ft per second per second is required to follow the wire. The pantograph pressure on the contact system will be decreased by about $12^1/_2$ lb where the acceleration is upward, and increased by a like amount where the acceleration is downward. In the first and last quarters of the span the pantograph will have a pressure of about $18^1/_2$ lb against the contact wire while in the second and third quarters the pressure will be $47^1/_2$ lb. This tends to increase the uplift at the center of the span and decrease it at the support.

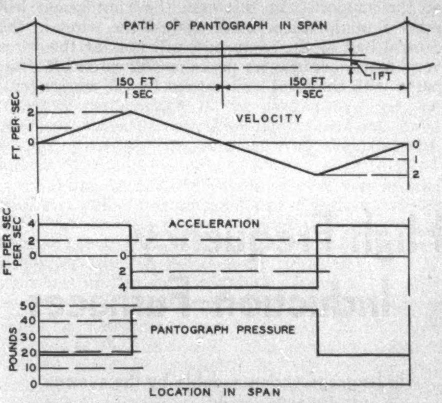

Fig. 7. Variation in pressure, acceleration, and velocity of pantograph B at a speed of 150 ft per sec over a typical 300-ft span

The assumption that the contact wire at the center of the span is lifted 1 ft higher than at the support in a 300-ft span is not an unusual condition nor is it necessarily a maximum condition. A single pantograph probably would not have enough pressure to lift this amount on most main line catenary systems but 3 or more pantographs close together, as when double-heading locomotives, could do it. Also the same condition can result from temperature changes. Any catenary system using a bronze or composite messenger will lift or sag more than 1 ft at the center of a 300-ft span when extreme temperatures are experienced. With a heavy catenary system the sagging at the center of the span due to high temperatures will bring about a condition where the pantograph will be more than 1 ft lower at the center of the span than at the support. In this case the pantograph will exert a minimum pressure against the wires in the central half of the span, and will not lift the wires very much because its pressure will be small compared with the total load carried by the messenger.

With so large a variation in the pantograph pressure against the contact wires at high speeds, under normal operating conditions any additional small irregularities in the contact system may require accelerations that would reduce or increase the pressure more and result in collection troubles. It is doubtful if current collection will be satisfactory on most present-day catenary systems, even with the latest designs of pantographs, at speeds of 100 mph or more. If speeds of this order are to be used, both the catenary system and the pantographs will have to be improved and designed for them.

High Frequency Induction Furnaces

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In language understandable by the average electrical engineer, this paper presents a brief outline of the theory of the electric induction furnace and of the application of that theory to the operating characteristics and limitations of such furnaces. From a metallurgical standpoint the chief advantages associated with the use of induction furnaces are: freedom from contamination of the melt, the high temperatures obtainable, and the circulation of the molten charge by the electromagnetic forces within it. The immediate acceptance by the industry of this comparatively new melting tool indicates that more extensive use of high frequency induced heat is to be expected in the future.

SO MUCH has been written on the subject of the high frequency electric induction furnace, particularly by Dr. E. F. Northrup, Ajax Electrothermic Corporation, Trenton, N. J., who may well be called the father of induction furnaces, that little of the original can be claimed for the conclusions reached. It is hoped, however, that the manner of presentation may appeal to many Institute members who are not already familiar with the subject. The appendix presents some interesting relationships between the operating characteristics and the size of the furnace in a very roughly approximate form, which may be of interest even to those already familiar with the subject.

An induction furnace is essentially a transformer, the secondary of which is the charge of metal to be melted. There are 2 principal types. First is the core or ring type, in which the charge forms a secondary circuit surrounding or ringing the magnetic core as in an ordinary power transformer. This type, which is adapted to low frequencies, will not heat up with a cold scrap charge but must be started with a complete or continuous secondary circuit of metal consisting of either a cold metal ring or a portion of the preceding molten charge left in the furnace for starting purposes.

The second type is the coreless furnace consisting usually of a helical inductor coil or primary winding and a cylindrical or nearly cylindrical crucible of refractory material concentrically located inside of the inductor coil. When supplied with electric power at a relatively high frequency this second type of furnace will melt easily a charge of cold scrap of any size. Even at 60 cycles such a furnace will operate satisfactorily except when starting with a cold scrap charge. It even will start cold at 60 cycles if supplied with a large plug of solid metal in the bottom of the crucible or hot with 25 or 30 per cent of the preceding molten charge left in for starting purposes.

The present paper deals entirely with this second or coreless type of furnace as applied to the melting of steels.

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The single-phase power required by these furnaces is usually supplied by a high frequency alternator driven by a polyphase motor. Frequencies vary, but in general do not exceed 2,000 cycles per second, while 2,000 volts appears to be the present safe upper limit of voltage applied to the primary winding. In regard to capacities of induction furnaces now in use, sizes up to 3,000 lb are common, while one plant at present is using a 4-ton furnace; it is believed that the future trend undoubtedly will be toward larger units. Power consumption varies greatly in different plants, but as low as 600 kwhr per ton of steel is claimed for large furnaces.

OUTLINE OF THEORY

When an alternating current flows through a metal conductor the distribution of the current density over the section of the conductor is never uniform. In the case of an isolated conductor the law of electromagnetic induction operates to yield the highest current density at the surface. When the frequency of the current and the permeability of the conductor are relatively high and the resistivity relatively low, the current will be confined largely to a thin surface layer or skin.

Theory shows that in such a case the problem may be handled as if the current were distributed uniformly over a skin depth of $T = \frac{1}{2\pi}\sqrt{\frac{\rho}{\mu f}}$, where ρ is the resistivity of the conductor in absolute cgs units, μ is its magnetic permeability, f is the frequency in cycles per second, and T is in centimeters. In this case the effective or equivalent a-c resistance of the conductor will be the resistance of the skin layer as defined, and its equivalent reactance will be equal to its resistance, this reactance being the portion due only to the flux within the skin layer and not to any flux outside of the conductor.

The preceding formula applies strictly only to the case of the current flowing through a flat plate of indefinite extent, but for practical purposes it applies with sufficient accuracy to a round conductor the diameter of which is large as compared with the skin depth; it applies also with sufficient accuracy to the cylindrical current flowing around the outer wall of the charge in a coreless induction furnace as well as to the primary current flowing around the inner wall of the inductor helix, although in none of these cases is it exact.

The only reasonably exact theory that can be applied to the high frequency coreless furnace is that involving Bessell's functions and even then only when the length of the helix is very large as compared with its diameter. In other words, in a furnace of normal proportions where the diameter and length of the helix are about equal, the end effect is large and complicated corrections have to be made in order to yield even fairly accurate results. The best attempt in this direction is given in a little book by C. R. Burch and N. R. Davis entitled "An Introduction to the Theory of Eddy Current Heat" published by Ernest Bent, Ltd., London, Eng.

Several other methods of attack have been employed, but the one that seems most suitable for the average electrical engineer is that which deals with the induction furnace in the light of conventional power transformer theory with some necessary variations. In this outline the charge will be assumed in the molten condition since any other condition renders the problem too complicated for practical purposes.

Although there is no available experimental data on the resistivity of molten steel, it will be sufficiently accurate to assume this to be 200 microhm-centimeters, which seems to give satisfactory results when applied to this problem. The magnetic permeability of the molten steel may be taken as unity. From these figures and the given frequency the equivalent skin depth then is calculated.

Assuming a cylindrical skin layer of current around the outer wall of the molten charge of such magnitude as to develop the desired amount of power in the charge, the resistance of the skin layer having been computed from its radial depth, resistivity, and dimensions of the crucible, this current will require an induced secondary voltage equal to the current times the resistance times $\sqrt{2}$, since the reactance is equal to the resistance. This secondary induced voltage must be produced by the vertical flux linking with the skin layer and passing through the cylindrical space within this layer. Its density then can be computed by the well-known formula. The exciting current can be computed by the familiar method, account being taken of the end or outside reluctance.

This gives the foundation for the equivalent transformer diagram, namely, the secondary voltage, the secondary current lagging 45° behind the voltage, and the exciting current 90° ahead of the voltage. From these 2 currents primary ampere turns may be computed.

Next compute the skin depth and resistance of the primary circuit reduced to a one-turn basis. Then compute the leakage reactance voltage of the primary due to the flux produced by the primary ampere turns, and passing through the annular cylindrical space between the primary and secondary current sheets. In making this calculation the end effect also must be considered. The primary voltage per turn then will be the sum of 3 components: (1) the voltage balancing that induced by the working flux which passes inside of the secondary current sheet; (2) the ohmic drop in the primary; and (3) the reactance drop in the primary. This will give the volts per turn from which the necessary number of turns can be computed according to the chosen supply voltage.

The copper loss, electrical efficiency, and power factor then may be computed by well-known methods.

This method of procedure makes no claim to theoretical rigidity but results check with experimental tests closely enough for all practical purposes.

The purpose of the outline at this point is chiefly to make more intelligible the discussion of the several vital factors given in subsequent portions of this paper by outlining the language to be employed. In an appendix a brief algebraic analysis of the general problem of design based upon this outline of theory is given.

SINGLE-PHASE VERSUS POLYPHASE FURNACES

The foregoing outline assumes a single-phase supply. Although many attempts have been made to design polyphase coreless induction furnaces, several fundamental considerations make them undesirable. As far as the authors are aware, no successful polyphase high frequency coreless furnace is in operation today. Therefore, it will be assumed that hereinafter this paper deals only with single-phase furnaces.

GENERATING EQUIPMENT

It will be assumed in this connection that the equipment in question is for a relatively high frequency, say approximately 1,000 cycles per second, since this frequency has become almost standard for this type of furnace in sizes employed for melting steel. The only dependable commercial supply at this frequency is the single-phase alternator usually driven by a polyphase synchronous motor although, of course, it would be possible to drive such an alternator either from a high speed steam engine or from a steam turbine.

For frequencies much higher than 1,000 cycles per second the inductor type of generator probably would be more satisfactory, everything considered, but it is very difficult to say at just what frequency this advantage would be realized. For very much higher frequencies individual furnaces of laboratory size with mercury gap oscillators often are employed. Small furnace units also have been made using electronic rectifier and inverter tubes for the generation of high frequency currents, but as yet this method has not been developed to a point of commercial practicability.

Since the power factor of this type of furnace is inherently low, ordinarily not much higher than 10 per cent, it is obvious that the capacity of a high frequency alternator to supply an induction furnace direct would be enormous—in fact, prohibitive. It is customary, therefore, to use capacitors to supply the large quadrature lagging current required by the furnace. The actual cost of these capacitors at 1,000 cycles is a small fraction of the additional cost that would be involved if the generator had to supply this lagging current direct. This relatively low capacitor cost is due, of course, to the high frequency; at 1,000 cycles it amounts to about $1.50 per kva, whereas at 60 cycles it is more nearly $20 per kva.

Thus, the generating or supply equipment consists ordinarily of a single-phase high-frequency alternator driven by a polyphase synchronous motor with a bank of capacitors adjustable by relatively small steps and connected in parallel with the furnace coil.

FREQUENCY

Although the factors involved in the choice of frequency are numerous, it will be sufficient here to discuss only those of major significance. Consider first the furnace itself in the light of the brief outline of theory already given. Assuming a certain power delivered to the charge of a given furnace, the resistance of the cylindrical skin layer of the charge will be proportional to the square root of the frequency, and the current inversely proportional to the square root of this resistance. Thus the current will be inversely proportional to the fourth root of the frequency and, therefore, will vary only slightly for moderate changes of frequency. Similarly, the induced voltage in the secondary or charge circuit will be directly proportional to the fourth root of the frequency and, therefore, nearly constant for moderate changes of frequency.

The flux density inside of the secondary current sheet will vary inversely as the frequency, and the exciting current likewise will be inverse to the frequency. In other words, for a high frequency the secondary current will be slightly smaller, the secondary induced voltage slightly larger, and the exciting current considerably smaller than for a low frequency; for moderate changes of frequency, the primary ampere turns will vary only slightly with the frequency, since the primary current is the vector sum of the exciting current and the negative of the load current.

If, however, the variation of frequency under consideration is a large one, for instance a jump from 960 cycles to 60 cycles, the secondary current at 60 cycles will be just double that at 960 cycles and the resistance $^1/_4$ so that the induced voltage will be $^1/_2$ and the exciting ampere turns 8 times as great; thus the total primary ampere turns will be more than twice as great for 60 cycles as for 960 cycles. However, since the copper skin depth at 60 cycles is 4 times as great, the resistance loss in the primary coil will be only slightly greater than at 960 cycles

Fig. 1. Pouring a heat of stainless steel from a 3,000-lb tilting type coreless induction furnace at the plant of The Babcock & Wilcox Company, Barberton, Ohio

by an amount depending upon the relative magnitude of the exciting current, that is, in its relation to the magnitude of the working or load current.

The other factor involved is the leakage reactance voltage of the primary winding. The total leakage flux will be proportional to the primary ampere turns which for 60 cycles will be somewhat more than double that for 960 cycles; but since the frequency in the latter case is 16 times that in the former, the reactance voltage at 960 cycles will be about 6 or 7 times as great. Thus, the power factor of the 60-cycle furnace is considerably higher than that of the 960-cycle furnace—in fact, more than double for furnaces of the same size and proportions.

To sum up, the low frequency furnace will have larger copper loss, lower efficiency, and higher power factor than the high frequency furnace.

Consider next the influence of frequency on the generating equipment and its first cost. Although the lower frequency means higher power factor and a somewhat smaller quadrature lagging current, it also means larger capacitors. In fact, the cost of the capacitors for complete neutralization or unity power factor on the generator, decreases with increase of frequency about proportionally to the $^2/_3$ power of the frequency. The cost of the generator itself, however, increases rapidly with increase of frequency, particularly when the frequency exceeds 400 or 500 cycles, and very rapidly when it exceeds 1,000 cycles. As it can be assumed that moderate changes in frequency do not seriously affect the furnace itself, it is obvious that there will be an optimum frequency from the standpoint of the first cost of the generating equipment, and that this optimum frequency will vary with the unit cost of the capacitors as well as with the unit cost of the generators.

It has been pretty fairly established that this optimum frequency for relatively large furnaces is about 1,000 cycles per second.

VOLTAGE

For furnaces of large size such as those under consideration, a high voltage is desirable in order to reduce the size of bus bars and other leads as well as to reduce the corresponding copper loss. At the same time, the necessity for some exposed conductors as well as the limitations in the insulation of the furnace coil itself make it necessary to keep the voltage within limits. Most of the plants of this type are operating with voltages of the order of 1,000 volts, but one of the largest plants in the country has been operating for several years at 2,000 volts without experiencing any trouble on this score. This is probably the safe upper limit.

PRIMARY OR INDUCTOR COIL

Already it has been explained that within the frequencies under consideration (excluding the extreme 60-cycle case) the number of ampere turns on the primary or inductor coil is practically independent of frequency, other things being equal. These primary ampere turns may be considered as a single current sheet flowing in the cylindrical skin wall of the primary helix, the radial depth of which skin is fixed by the frequency. It is thus obvious that the primary copper loss within the frequency range under consideration also is fixed. As a matter of fact, while the ampere turns increase slightly with decreasing frequency, skin depth also increases although to a less extent, and the copper loss is more nearly constant than the total ampere turns. This statement holds true regardless of the voltage and the number of turns, except insofar as the higher voltage and larger number of turns involve a corresponding increase in the total vertical height of the insulation between turns thereby reducing the effective vertical height of the skin section through which the total current flows. This difference is small within the range of voltage considered.

Because this practically fixed copper loss is relatively high, it has been found very difficult to keep the temperature of the primary coils within reasonable limits by any other method than that commonly employed, namely, water cooling. The conductor is made in tubular form, sometimes circular and sometimes rectangular, and is wound as a simple helix with water circulating through the conductor.

In furnaces of the sizes under consideration, excluding the 60-cycle furnace, and with voltages as previously indicated, the number of turns is relatively small, say from 10 to 20, and the coil is wound in a single layer. As the skin depth in copper at 1,000 cycles is approximately 0.1 in., it is obviously useless to make the tube wall much thicker than that except for mechanical reasons.

This type of coil is practically universally used in high frequency coreless induction furnaces of the sizes under consideration. However, complete calculations have been made looking toward the possibility of employing what may be called a "band wound" coil in which each conductor consists of a thin sheet of copper with a width equal to the full vertical height of the coil, and the several turns wound concentrically one over the other with a thin layer of refractory insulation between them. In this case the distribution of current across the radial thickness of each conductor will differ materially according to the location of the conductor from the inside to the outside, and this difference may be so great as to produce a total copper loss even greater than that of the simple helical coil although the apparent skin section is increased enormously. In other words, the ordinary skin depth approximation no longer holds; in fact, in some of the turns current will be flowing in opposite directions on the 2 sides of the same sheet or band. Moreover, there will be an uneven vertical distribution of current in the individual sheets. For each number of turns there will be an optimum thickness of sheet, and it is possible to design such a coil for say 1,000 cycles that will have a copper loss approximately half that of the conventional helical coil; but as it is practically impossible to water-cool a coil of this kind, and as air cooling makes necessary vertical annular spaces between the individual turns or groups of turns of the coil—an arrangement involving considerable structural complications and expense, it has not as yet been developed into a commercially satisfactory design.

SHIELDING

One of the practical difficulties in the design of this type of furnace arises from the fact that the relatively powerful high frequency magnetic field throughout the region of the furnace structure causes induced parasitic currents in any metal parts of that structure. Therefore, it has been necessary to reduce these metal parts to a minimum and to design them so as to reduce parasitic currents in the individual parts. At best the losses in these parts are appreciable although probably not more than 1 per cent or possibly 2 per cent.

In order that a substantial external steel supporting frame may be used without incurring excessive losses, it is possible to shield the frame from any considerable stray field by employing a closed copper tertiary or shield circuit inside of the frame, this circuit consisting of a thin copper cylinder concentric with the inductor coil, but far enough outside of it to permit the total magnetic flux of the furnace to pass between the inductor coil and the shield without the necessity for any excessive shielding current.

The magnitude of this shielding current can be computed easily from the furnace design since its magnetomotive force for perfect shielding will be equal to the drop of magnetic potential due to the total flux as it passes through the annular space between the inductor coil and the shield. It is thus obvious that the larger the diameter of the shield for a given sized inductor, the lower will be the flux density in this annular space and the less the shielding current. Moreover, since the shield current will be confined to the same skin depth as that of the current in the main coil, there can be no gain by making this shield thick. If the shield is of insufficient diameter the shield copper loss may be more than the parasitic losses that are eliminated. As a matter of fact, such a shield is practically useless from the standpoint of efficiency unless its diameter is considerably larger than is permissible on the ordinary furnace. Moreover, in such a case, while the outside steel structure may be completely shielded it cannot carry the inner structure without some supporting connection, and it is practically impossible to provide such a supporting connection without metal parts within the region of the main magnetic field, particularly on the top of the structure.

In lieu of a complete cylindrical shield such as described, flat copper plates sometimes have been employed on the 4 sides of a square frame. While this arrangement is claimed to be fairly satisfactory, no quantitative evidence is available.

If the full thickness of a thick copper shield could be employed for current conduction, the shield problem would be a fairly simple one. It would be possible, of course, to employ a multiple layer band shield, such as described for the primary "band wound" coil, with the outer and inner ends connected by stranded conductors passing through holes in the several layers. If properly designed such a shield would reduce the shield loss considerably, but its complications involve considerable expense and this expense hardly is warranted by the power saved. It is thus unlikely that any of the shielding schemes thus far proposed result in any considerable saving in the structural losses.

MAGNETIC YOKES

In order to reduce the reluctance of the return path, experiments have been made with magnetic yokes consisting of vertical stacks of laminated steel just outside of the inductor coil, running downward from the top of the coil and underneath the bottom of the furnace until they come together. These yokes improve the power factor by reducing the exciting current; but since in high frequency furnaces the exciting current represents a relatively small part of the total reactive kilovoltamperes, and since the reluctance of the return magnetic circuit is a small part of the total, the gain is very small. Moreover, since such yokes also reduce the reluctance of the return part of the leakage path they increase the leakage reactance of the primary coil enough practically to balance the gain in exciting current; thus, for high frequency furnaces the increased cost and structural complications are not warranted by the doubtful gain in power factor.

In the 60-cycle furnace, however, where the exciting current is many times larger and the leakage reactance small, considerable improvement in the power factor is possible and such yokes are at present in successful operation on at least one 60-cycle furnace. It is interesting to note that in this case the yoke provides the opportunity for using a copper shield of much smaller diameter than is possible without the yoke; the 60-cycle furnace referred to has such a shield in successful operation with a very substantial steel frame surrounding it. The structural strength of such a furnace is excellent. (See Fig. 3.)

POWER FACTOR

Power factor of an induction furnace of any given frequency depends largely upon the ratio of the inner diameter of the primary coil and the outer diameter of the charge. Unfortunately, the necessity for a considerable radial depth of a refractory lining within this space makes the power factor of such furnaces very low. For example, at 1,000 cycles it will vary from 10 to 12 per cent within the size range under consideration, although it is possible to increase these values considerably by employing a thinner lining. This, however, would increase greatly the risk of a run-out, which is an expensive procedure particularly if the molten metal damages the inductor coil.

During actual operation the lining varies considerably in radial depth because of its erosion. When this erosion reduces the thickness to a danger point it is reinforced on the inside to its maximum thickness. Thus the power factor will vary from maximum to minimum with lining wear and the maximum often will exceed considerably the values given in the preceding paragraph.

ELECTRICAL ASPECTS OF MELTING A CHARGE

When starting cold the initial secondary heating currents are induced in the individual pieces of scrap, since the resistance at the contacts between the several pieces is sufficient to prevent any considerable circuital currents around the charge as a whole. At low frequencies, say 60 cycles, it is practically impossible to get a magnetic field strong enough to generate the necessary currents in individual pieces of a charge unless these pieces are unusually large, even though the cold permeability of the steel may be very high. At the higher frequencies no such difficulty arises, although even with these higher frequencies it is not ordinarily possible to deliver as much power to the cold charge with the same voltage impressed upon the primary coil as will be absorbed when the charge is in the molten condition. On this account it is usually necessary during the starting period to increase the primary volts per turn. This makes necessary the provision of 1 or more, usually 2, additional taps on the primary coil with the necessary switches, preferably on the switchboard itself for the convenience of the operator. These taps usually are connected to one of the generator leads. Thus, the furnace coil acts as a step-up autotransformer to increase the voltage at the inductor terminals and hence across the capacitors which are connected in parallel with the inductor.

Fig. 2. Tapping a heat of stainless steel from a 3,000-lb stationary coreless induction furnace with bottom tap-hole. Compare the size of this furnace with that shown in Fig. 1, and note rugged appearance of stationary furnace

It is fairly obvious that during the starting period when the permeability of the steel is high, the exciting current will be reduced considerably, the power factor increased, and a smaller number of capacitors required. In other words, the number of capacitors required for complete neutralization will vary considerably from the cold starting to the finish of the heat; the maximum change takes place when the temperature of the metal passes the recalescence point and its permeability drops to unity. However, this change does not take place in all the metal at the same time so that the change of power factor as a whole is fairly gradual.

It is also obvious in this connection that the cold starting power absorbed will depend not only upon the size of the pieces of scrap but also to some degree upon the total amount of metal in the initial charge, which with odd shaped scrap may be less than $^{1}/_{3}$ of the final charge. It is thus possible with badly shaped scrap that the initial power in starting may be low even when the lowest tap is employed on the primary coil.

Electromagnetic reactions within the molten charge of the coreless induction furnace are such as to cause a stirring or boiling of the metal which increases at low frequency, since in that case both the secondary current and the magnetic field within the bath are larger, the same power being assumed. It is obvious that at any given frequency the amount of stirring would be approximately proportional to the square of the power delivered. The charge circulates in 2 distinct zones, 1 in the upper and 1 in the lower half of the furnace.

Although it would be entirely possible to supply sufficient power to a furnace of this type to complete the melting in less than one hour, there are some objections to rapid melting. When a heat is started at a high rate, portions of the metal quickly become molten and run to the bottom of the crucible. Because this molten layer receives more power than any similar quantity of the unmelted scrap it becomes superheated, boils violently, oxidizes readily, and causes serious erosion in the bottom of the furnace. Moreover, a solid lump of steel in the middle of this molten metal receives less power than it would before the molten metal was present, because it is shielded by the circular current around the wall of molten pool. Thus it receives heat mostly by conduction and melts rather slowly, while the metal surrounding it is superheated. Obviously, then, there is a limit to the melting time below which it is undesirable to go. On the other hand, the total heat leak obviously increases with the time of heating since the average temperature throughout the melting period is nearly constant. Thus we find again the necessity for some compromise or happy medium in the melting period, and a little consideration will indicate that the larger the furnace the longer should be the melting period. For small furnaces, of say 500-lb capacity, this period may be as short as 1 hour; but as the size increases, it is desirable to increase the melting period to 2 or 3 hours.

SIZE LIMITS

Although no experience has been had with furnaces of this type which indicated any difficulty on the score of size, the following considerations would indicate a difficulty that might arise in furnaces of large diameter.

Since the total charge of a furnace of this type never can be held by the crucible in cold scrap form, it is necessary to keep feeding in scrap as the melt proceeds. Imagine a large piece of this cold scrap dropped into the center of the molten pool. As this piece would receive heat almost solely by conduction as already indicated, it might take so long in melting that the molten pool surrounding it would be superheated for a considerable period before the cold piece was thoroughly melted. This could be prevented, of course, by slowing down the heat and lengthening the melting period; it is for this reason that large furnaces must have a longer melting period. It is thus conceivable that a diameter may be reached which corresponds to a melting period too long for commercial efficiency. However, this limit has not been reached yet and experience alone can tell what the maximum diameter of the crucible may be; it is, of course, possible that no such limit will be reached on this particular score.

The influence of size and diameter upon several other operating characteristics and factors of interest is considered more quantitatively in an appendix.

LININGS

For lining small induction furnaces, users prefer a one-piece crucible with heat insulation between crucible and coil. This type of lining, however, is very expensive for large furnaces, and several methods for installing built-in linings have been devised with varying degrees of success. The patented Rohn process produces a fritted lining by fritting a tamped refractory which has been placed between the coil and a steel sleeve. A modification of this method uses an asbestos sleeve in place of the steel sleeve. In both methods the steel sleeve or asbestos sleeve is fused away during the first heat. A third type of lining used extensively consists of a bonded refractory rammed in the furnace without the use of a sleeve. Fritted magnesite, acid ganister, or quartz linings may be produced by these methods.

Linings may be acid, basic, or neutral, magnesite commonly being used for a basic lining, zircon for a neutral lining, and ganister or a silica sand for an acid lining. Excellent results have been obtained using very pure silica sand of suitable grain size mixed with 15 per cent silica flour and moistened to a ramming consistency with a silicate of soda solution.

The life of the lining depends upon numerous factors. A highly refractory basic lining of sintered magnesite probably will give longest life if the lining can be handled so that cracks do not develop from sudden thermal strains. Magnesite linings may crack also due to bridging of the charge during melting with resultant heating of the metal below the bridge, or due to large pieces of scrap expanding. Magnesite linings do not flux appreciably. The average life of magnesite linings in 400- and 600-lb furnaces is 30 to 35 heats in the melting of stainless alloys. Neutral zircon linings have not been found generally satisfactory within the somewhat limited experience of the authors with this type of refractory. The ganister or silica sand lining is not as refractory as the magnesite or zircon linings, but will stand temperatures up to 3,000-deg F for short holding periods, and this limiting temperature is sufficiently high for most steel foundry melting. Acid linings do not crack readily, but wear away gradually by fluxing. With proper handling the acid or silica sand lining will give more than 100 heats of miscellaneous alloy melting before a complete new lining has to be installed. The bottom half of the lining usually requires patching after 10 or 15 heats because of the more severe erosion in that zone. Acid linings have a decided cost advantage over basic magnesite or neutral zircon linings, ganister being approximately $18 per ton as compared with $100 to $240 per ton for magnesite and zircon.

The question of correct grading of the dry refractory material is very important in securing satisfactory lining life, this subject being covered in a paper "Refractory Materials for the Induction Furnace" by J. H. Chesters and W. J. Rees. The refractory problem in the high frequency furnace has been one of the hardest problems to solve in the development of this furnace because of the high temperature gradient within the lining and because of the terrific thermal stresses set up during the tapping of a heat.

METALLURGICAL CONSIDERATIONS

The most interesting and important metallurgical features of the induction furnace are:

1. Freedom from contamination of the melt by reason of the absence of products of the heating process.
2. The high temperatures attainable.
3. The circulation of the molten charge due to electromagnetic forces within the bath.

All other characteristics of induction furnace melting, such as rapidity of melting, are subsidiary, and the field of application of the induction furnace has been governed largely by these 3 characteristics.

The first 2 characteristics have resulted in the application of the induction furnace to the production of low carbon alloys such as low carbon stainless irons and magnetic alloys; to the melting of highly refractory melts such as tungsten, molybdenum, cobalt, chromium, and alloys thereof; and to the production of tool steels, high nickel alloys, and corrosion and heat resisting iron-chromium or iron-nickel-chromium alloys. Considerable tonnage of low carbon stainless iron is produced by remelting scrap of corresponding analysis which could not be reclaimed conveniently by any other melting process. The great flexibility of induction furnaces in changing from heat to heat of varying analyses is of de-

Fig. 3. Sixty-cycle 1,000-lb furnace of the shielded yoke type at the left. High frequency 1,000-lb furnace at the right; note experimental bottom-tap spout on this furnace

Note the relatively rugged structure of the 60-cycle shielded-yoke type of furnace. The 3 control panels are, left to right: 60-cycle furnace control; motor panel for high frequency motor-generator set; furnace control panel for high frequency 150-kva furnaces

cided advantage in producing alloys of the foregoing types which are melted in comparatively small sized heats and usually produced in a large variety of compositions.

Mention already has been made of the effect of rapid melting on the behavior of the first pool of molten metal formed which rapidly may become superheated, resulting in rapid oxidation of the metal and in abnormal reactions between the metal and the refractory lining. This may be remedied to some extent by limiting the rate of heating and by sprinkling the hot but unmelted pieces with slag forming material to prevent undue oxidation. The local overheating of the first molten metal may be avoided also by leaving in the furnace sufficient molten metal from the previous heat when the chemical natures of the 2 successive heats are not in conflict. Where successive heats of radically different compositions are to be melted, it may be necessary to melt an intermediate wash heat of low carbon iron to prevent contamination of the second melt from the slight "skull" left in the furnace from the previous heat.

Agitation of the metal after complete melting must be controlled to prevent boiling up of the molten metal through the slag covering with resultant exposure of the molten metal to the air. This movement in the low frequency furnace is particularly violent as evidenced by a nitrogen content of 0.117 as compared with a nitrogen content of 0.030 for the same type of alloy (18 per cent chromium, 8 per cent nickel) melted in a high frequency heat. Fortunately, movement of the bath can be controlled readily within limits by the regulation of the power input.

The possibility of refinement of molten metal under a slag in the induction furnace was recognized early, and many papers have been published showing the rapid removal of carbon, phosphorus, and sulphur under oxidizing and reducing slags. The elimination of oxygen from steels made in the induction furnace, however, is of much greater importance than the elimination of these metalloids, and presents great although not unsurmountable difficulties. Refinement of a metal under a slag in the induction furnace is aided by the agitation of the metal and is restricted by the quiescence and low temperature of the slag. The low temperature of an induction furnace slag could be overcome by supplying an auxiliary heating unit such as an arc or burner just sufficient to maintain the slag at the proper temperature. This expedient is probably unnecessary, however, if slags are employed which have a melting point so low as to remain liquid by transfer of the heat from the surface of the molten metal bath. Regardless of the melting point of the slag, provided it is lower than that of the melt, the slag layer at the interface of the melt surface and the slag is at the same temperature as the metal bath, and therefore is molten. Reactions between this slag layer and the bath proceed and are aided by the agitation of the melt, so that rapid attainment of equilibrium between the slag and melt is produced.

Choice of slag naturally will depend upon whether a basic or acid lining is used, and upon the nature of the alloy being melted. The use of slag possessing a high fluxing power for iron oxide or chromium oxide in the case of the corrosion resisting and heat resisting alloys is favored. Ground sodium silicate separated from the surface of the lining by an outer ring of silica is being used with success in furnaces having acid linings. Various lime-silica mixtures may be used with both acid and basic linings. Small additions of fluorspar may be made to the slag.

Deoxidation of the metal in the furnace is produced through the slag, i. e., the deoxidizer in finely ground form is mixed intimately with the ground materials of the slag makeup. That this procedure is quite effective in producing a reducing slag and a deoxidized condition of the metal may be shown by the control analyses of the slags of a stainless 18 per cent chromium, 8 per cent nickel heat made in a basic magnesite lined high frequency furnace which had ferrous oxide (FeO) contents of 16.01, 4.90, 2.20, 2.01, and 1.70 per cent in 5 successive slags removed during the refining period of 1 hr, 40 min of the heat.

Basic induction furnace slags have been produced with low oxide content. An analysis of a final refining slag of this type compared with a typical slag from a basic electric arc furnace, both on a low carbon stainless steel, is as follows:

	Basic Induction Furnace Slag	Electric Arc Furnace Slag
Silica	28.30	31.00
Lime (CaO)	57.68	56.00
Iron oxide (FeO)	0.28	Undetermined
Chromium oxide (Cr_2O_3)	0.13	0.80
Manganese oxide (MnO)	0.32	0.50
Magnesia (MgO)	10.97	3.00
Alumina (Al_2O_3)	Undetermined	4.00
Fluorine	Undetermined	4.00

The analyses of these slags are approximately the same, and refinement of the metals in both furnaces should proceed to the same degree provided final establishment of equilibrium between the slag and metal is permitted in each case. Acid slags may be worked similarly, the analyses of 4 successive slags from a 1,500-lb heat of 18 per cent chromium, 8 per cent nickel iron in a ganister lined furnace being as follows:

	Slag 1	Slag 2	Slag 3	Slag 4
Silica (SiO_2)	58.15	54.62	60.04	58.01
Lime (CaO)	32.88	40.50	32.14	29.04
Iron oxide (FeO)	2.20	1.82	0.87	0.30
Chromium oxide (Cr_2O_3)	1.30	2.39	2.39	5.10
Manganese oxide (MnO)	1.08	1.59	2.11	5.72
Magnesia (MgO)	0.46	0.44	0.72	1.02

The greater deoxidizing ability of the acid-lined furnace in melting steel of this composition readily is shown by the analyses of the 4 slags in which the chromium and manganese contents increase with each succeeding slag. On the other hand, the ferrous oxide (FeO) content of the slag is reduced with each succeeding slag. One of the difficulties of working a heat under a slag in an induction furnace lies in the considerable erosion of the furnace lining around the slag zone.

The rapid agitation of the metal, which serves in hastening reactions between metal and slag and thus in refining the melt, produces an accompanying disadvantage in attempting to produce steel of low sonim content. Slag particles are drawn into the melt by the agitation, and it reasonably may be expected that the particle size of the entrained slag is small and kept small by the rapid movement of the bath. It is well known that the particle size of the slag is the most important factor in the elimination of slag inclusions, and, unless coalescence of the slag particles occurs, the steel produced will show a high inclusion count under microscopic examination. Due to the rapid agitation generally present in induction furnace melting, the slag particle size is small, the inclusions therefore are not elimininated readily, and the induction furnace steels are generally somewhat less clean than electric arc furnace steels. An inclusion count of several induction furnace and arc furnace steels of the same analyses show values of 0.13 to 0.53 and 0.087 to 0.13 for the area occupied by inclusions in per cent of total area of field examined under the microscope for the 2 types of steel, respectively. That clean induction furnace melted steels may be produced is evidenced by the values of the inclusion count on the low side of the range just given.

It should be appreciated also that the rate of coalescence of the slag particles depends upon the chemical nature of the slags. The governing factors in the coalescence of inclusions have been described by Herty and his co-workers, and a complete study of this problem as applied to induction furnace melting would be extremely valuable. Some evidence is available to show that the slag particles of basic furnace induction heats are generally larger than those of acid heats, and that basic heats are slightly cleaner than acid heats, due probably to more rapid coalescence and elimination of the basic slag particles as compared with the glassy acid slag particles.

No difficulty is experienced in melting steel of any composition in this type of furnace. No excessive loss of the usual alloying elements occurs with the exception of the readily oxidizable elements such as silicon, manganese, and aluminum, which are present only in small quantities in the usual commercial steels, and the loss of which can be compensated readily by small additions previous to tapping. The normal chromium loss in melting 18 per cent chromium, 8 per cent nickel irons either from scrap or virgin materials is only 0.5 per cent. The type of lining will be governed largely by the type of metal melted and by the affinities of the elements of the melt for oxygen as related to the stability of the oxides, magnesite, or silica, of the basic or acid linings. Alloys containing appreciable quantities of aluminum, vanadium, manganese, and other elements of high affinity for oxygen are melted in magnesite linings to prevent the undue loss that would occur in acid lined furnaces.

In view of the fact that induction furnaces require a comparatively short melting period, it is not feasible to take samples of a heat prior to tapping for check analysis. Induction melting, therefore, requires that the analysis of the charge be known exactly, and careful handling and sorting of scrap for the storage bins is required. Very little trouble has been experienced on this score at the plant of The Babcock & Wilcox Company in spite of the fact that this plant regularly produces alloy steels of some 30 different compositions and a much larger number of special alloys. Heat after heat of a given composition within a limited range for the individual elements may be produced by induction furnace melting. Ten successive heats of a 4–6 per cent chromium, $^1/_2$ per cent molybdenum steel showed but slight variations in the amounts of the individual elements, the spread of the percentage contents over the ten heats being as follows:

Carbon	0.24
Manganese	0.11
Silicon	0.15
Chromium	0.34
Molybdenum	0.37

Experience of the authors has been limited to furnaces of 3,000-lb maximum capacity. The future trend undoubtedly will be to larger melting units; one steel plant is using at present a 4-ton furnace, and it is expected that the use of these larger units will simplify greatly the problems arising from the rapid agitation of the molten bath of small induction furnaces. With these larger melting units a better comparison then may be made between induction furnace melting and other steel melting processes in units of approximately equal tonnage.

COMMERCIAL COST COMPARISONS

The investment cost of high frequency melting equipment is roughly 4 times as great as the investment cost of arc melting equipment on a comparative daily tonnage basis; but this cost alone does not give a fair picture. The melting of small heats at frequent intervals is often very advantageous in that the building space required for mold capacity is reduced very much; the outlay for ingot molds is less, the capacity of handling equipment such as overhead cranes and hoists may be reduced considerably. Also, in ingot production, it is quite probable that soaking furnace equipment might not be as costly, due to size for induction melting. D. F. Campbell claims that the capital cost for a steelworks of 6,000 tons per week capacity would be less if induction melting equipment were used in place of open-hearth furnaces. Moreover, the operating advantages would be numerous due to the flexibility of the induction equipment.

Power consumption varies greatly in different shops due to variation in steel making practices. Many users of induction furnaces claim as low as 600 kwhr per ton for large furnaces. In general it is probably true that arc melting is somewhat less costly from a power consumption standpoint but the added cost for electrodes more than balances the difference. Moreover, the arc furnace load is less desirable on a demand basis compared with a synchronous motor driven load for the induction furnace. The power factor of the load is better and the load fluctuations are not as great for the induction equipment.

Based upon an approximate monthly production of 200 tons melted in 3,000-lb and 1,500-lb furnaces using a 1,250-kva 960-cycle generator, the cost of acid furnace linings at one plant is approximately $1.30 per ton. On the same tonnage basis the cost of maintenance for the entire melting equipment, exclusive of furnace linings, is about $0.90 per ton. For smaller melting units or for a smaller tonnage these figures, of course, would be higher.

Fig. 4. High frequency motor-generator sets in the plant of The Babcock & Wilcox Company, Barberton, Ohio

1,250-kva 960-cycle set in foreground; 150-kva 2,040-cycle set in background. Note oil filled condenser tanks and magnetic contactors in 2 banks on either side of control switchboard

Continuity of production with induction melting usually is maintained by having a spare furnace on hand so that lining repairs may be made without loss of time. The cost of a spare unit adds only about 5 per cent to the original investment.

The question of metal loss during the melting operation is of minor importance, but over a long period of time it might amount to a considerable sum. No rigid data on melt loss in induction furnaces is available; but it is safe to say that such loss is in all probability considerably less than in other types of melting equipment. This is because the metal is the hottest part of the furnace and, moreover, the melting time is usually very much less. Hence, less loss by oxidation and through slagging operations takes place.

The immediate acceptance by the industry of this comparatively new melting tool indicates that more extensive use of high frequency induced heat is to be expected. In addition to advances in melting equipment, future development is likely to reveal new economies and uses for this type of heating in continuous furnaces for heat treating and processing of steel and other metals. Doctor E. F. Northrup in his paper "Practical Methods for Inductively Heating Solids," presented at a meeting of the Association of Iron and Steel Electrical Engineers in January 1933, offers some interesting and ingenious methods of employing high frequency heating.

The first commercial installation of high frequency melting was a 150-kva unit installed some 7 years ago. The development in this short period has been rapid, and today 2 generating units of 1,250-kva capacity are in operation in 2 large midwestern plants; numerous other units of intermediate sizes have been installed in plants scattered throughout the country. Only time can tell what the future holds in store for induction heating.

Appendix I—Relation of Size to Electrical Characteristics

The purpose of this appendix is to give a rough idea of the relationship between the electrical characteristics of the furnace and a basic linear dimension, namely, the inner diameter of the crucible. To this end, all other dimensions are assumed to bear a constant relation to this diameter within the range of sizes considered, namely, from 1 to 4 tons capacity. This assumption of constant proportions does not accord strictly with design practice, but is close enough within the range of sizes under consideration. It is assumed also that the frequency in every case is 960 cycles per second.

In order to reduce the results to their simplest form, it has been necessary to make some rather crude approximations. This does not involve any appreciable error for the 2-ton size of furnace, the error for the limits of the range being given in each case.

The only result that might seem a little abnormal is in connection with the power factor, which is found to vary roughly inversely as the diameter. In an actual design the thickness of the refractory wall would not increase quite as rapidly as the diameter, which, together with some of the approximations made, would tend to make the power factor more nearly constant. If, for example, the refractory wall were of constant thickness for the different sizes, the power factor would be constant, although the omission of the approximations would make it even a little larger for the larger sizes. With normal designs, the power factor actually would be a trifle smaller for the larger sizes.

In any case, it must be remembered that the approximations apply only to the size range mentioned, and cannot be extended beyond this range without serious error. Another assumption which, although in general rational, is nevertheless not strictly according to practice, is that the melting time is proportional to the diameter according to a particular numerical ratio. All of these assumptions and limitations must be borne in mind when interpreting the results.

Consider only from 1-ton to 4-ton size range. In order to simplify otherwise complicated expressions, assume proportional dimensions. (This assumption, while not strictly according to actual designs, is close enough within the range considered.)

Let

d = mean outside diameter of charge (inches)
d_1 = inside diameter of coil = approximate diameter of skin current
t_r = radial thickness of lining = $0.12d$
l = vertical height of inductor = vertical depth of charge
$l/d_1 = 0.9$, or $l = 0.9d_1 = 1.115d$
V = volume of charge (cubic inches)
W = weight of charge (pounds)

Then

$$d_1 = d + 2t_r = d + (2 \times 0.12d) = 1.24d$$

$$V = \frac{\pi}{4} d^2 l = \frac{\pi}{4} d^2 \times 1.115d = 0.875d^3$$

$$W = 0.27V = 0.236d^3$$

Allowing for heat leakage and radiation, total gross heat to charge $= 230W$, in watt hours.
Let T = total melting period in hours $= 0.075d$ (estimated from experience)

Then average power to charge, $P_{2A} = \frac{230W}{T} = \frac{230 \times 0.236d^3}{0.075d} =$ $727d^2$ watts
And maximum power to charge at full melt $= P_2 = 1.375P_{2A} =$ $1{,}000d^2$ watts (the 1.375 is an estimated constant)
Assume
Frequency, $f = 960$ cycles per second
Resistivity of molten charge $= \rho_2 = 200 \times 10^{-6}$ ohm-cm
Magnetic permeability of molten charge $= \mu = 1$

Then charge skin depth, $t_2 = \frac{1}{2\pi}\sqrt{\frac{\rho_2 \times 10^9}{\mu f}} = 5030\sqrt{\frac{\rho_2}{\mu f}} =$ 2.30 cm = 0.903 in.

Secondary resistance, $R_2 = \frac{\rho_2 \times l_2}{A_2} = \frac{\rho_2 \times (d - t_2)\pi}{l \times t_2 \times 2.54}$

$$= \frac{(200 \times 10^{-6})(0.965d)}{1.115d \times 0.903 \times 2.54} = 2.37 \times 10^{-4}$$

ohms (error < 1 per cent)

$(d - t_2) = 0.965d$ within 1 per cent error within size range considered; an approximation.

Secondary current, $I_2 = \sqrt{\frac{P_2}{R_2}} = \sqrt{\frac{1000\,d^2}{2.37 \times 10^{-4}}}$

$= 2{,}055d$ (error < 0.5 per cent)

Secondary voltage, $E_2 = \sqrt{2} \times I_2R_2 = 0.707 \times 2{,}055d \times 2.37 \times 10^{-4}$
$= 0.688d$

But $E_2 = 4.44 \times B_{2M} \times S_2 \times f \times 10^{-8}$
where
B_{2M} = maximum flux density linking charge
S_2 = area of flux path in charge

$$= \frac{\pi}{4}(d - 2t_2)^2 = \frac{\pi}{4}(d - 1.8)^2 = \frac{\pi}{4}(d^2 - 3.6d + 3.24)$$

$= 0.785\,(d^2 - 3.5d)$ (approximation, error < 4 per cent)
$= 0.785d\,(d - 3.5)$

Then

$$B_{2M} = \frac{0.688d \times 10^8}{4.44 \times 0.785d\,(d - 3.5) \times 960} = \frac{20{,}600}{d - 3.5} = \frac{20{,}600}{0.865d}$$

$= \frac{23{,}800}{d}$ (approximation, error < 4 per cent)

Primary exciting ampere turns, $NI_0 = 0.221\,B_{2M} \times l \times K_0$
where $K_0 = 1.5$ is a constant to account for the end and return path reluctance
Then

$$NI_0 = \frac{0.221 \times 20{,}600 \times 1.115d \times 1.5}{(d - 3.5)} = \frac{7{,}620d}{(d - 3.5)} = \frac{7{,}620d}{0.865d}$$

(roughly)

$= 8{,}810$ ampere-turns (approximation, error < 4 per cent)

Since NI_0 is only 12 to 18 per cent of NI_1 (total ampere-turns) the approximate value will serve the purpose of this general analysis.

$NI_1 = I_2 + 0.75NI_0$ (very closely for range and conditions assumed)
$= 2{,}055d + 0.75 \times 8{,}810$
$= 2{,}055d + 6{,}608$
$= 2{,}055\,(d + 3.22)$

NI_1 = approximately $2{,}055\,(d + 0.125d) = 2{,}310d$ (approximation, error < 3.2 per cent)

Primary copper loss:
Resistivity of copper at 90 deg C $= 2.2 \times 10^{-6}$ ohm-cm $= \rho_1$

Skin depth $= t_1 = 5{,}030\sqrt{\frac{2.2 \times 10^{-6}}{1 \times 960}} = 0.241$ cm $= 0.0950$ in.

R_1' = equivalent resistance of single-turn inductor $= \frac{R_1}{N^2}$ where
N = number of turns

$$R_1' = \frac{\rho_1 \times l_1}{A_1}$$

where l_1 = mean length of path of primary current, and A_1 = mean area of cross section of primary current path
$A_1 = K \times t_1 \times l$ where $K = 0.85$ to account for insulating space factor between turns
Then

$$R_1' = \frac{2.2 \times 10^{-6} \times \pi\,(d_1 + t_1)}{Kt_1l}$$

$$= \frac{\pi \times 2.2\,(1.24d + 0.0950)}{0.85 \times 0.0950 \times 1.115\,d + 2.54 \times 10^6}$$

$$= \frac{30.4\,(1.24d + 0.0950)}{10^6 \times d} = \frac{37.5\,(d + 0.0766)}{10^6 \times d}$$

$$= \frac{37.5(d + 0.003d)}{10^6 \times d} = 37.6 \times 10^{-6}$$

(approximation, error < 0.1 per cent)

$$I_1^2R_1 = (NI_1)^2\frac{R_1}{N^2} = (NI_1)^2R_1' = \frac{37.6}{10^6} \times [2{,}055\,(d + 3.22)]^2$$

$= 37.6 \times 4.22\,(d + 3.22)^2$
$= 158.7\,(d + 0.125\,d)^2$
$= 201.0\,d^2$ (approximation, error < 6.0 per cent)

Electrical efficiency $= \frac{P_2}{P_2 + I_1^2R_1} = \frac{1{,}000d^2}{1{,}000d^2 + 201d^2}$

$= 83.3\%$ (error < 1.0 per cent)

Primary reactance volts:
B_{lM} = Primary leakage flux density

$$= \frac{3.2\,NI_1 \times \sqrt{2}}{l \times K_l}$$

where $K_l = 1.35$ is a constant to account for the end and return field reluctance.

$$B_{lM} = \frac{3.2 \times \sqrt{2} \times 2{,}310d}{1.115d \times 1.35} = 6{,}940$$

(approximation, error < 3.2 per cent)

$\frac{E_x}{N}$ = Reactance volts per turn

$= 4.44 \times f \times B_{lM} \times S_l \times 10^{-8}$

where S_l = area of leakage path $= \frac{\pi}{4}(d_1^2 - d^2) = \frac{\pi}{4}d^2(1.24^2 - 1^2)$

$= 0.422\,d^2$

$$\frac{E_x}{N} = 4.44 \times 960 \times 6{,}940 \times 0.422d^2 \times 10^{-8}$$

$= 0.1248 \times d^2$ (approximation, error < 3.2 per cent)

$\frac{E_1}{N}$ = Total primary volts per turn (neglecting small primary IR drop)

$= \frac{E_x}{N} + 0.83E_2$ (very close for range and conditions assumed)

$= 0.1248d^2 + 0.688d \times 0.83$
$= 0.1248d\,(d + 4.57) = 0.1248d\,(d + 0.178d)$
$= 0.1470d^2$ (approximation, error < 7.1 per cent)

$$\text{Power Factor} = \frac{P_2 + I_1^2R_1 + (\text{stray losses})}{\frac{E_1}{N} \times NI_1}$$

$= \frac{1{,}000d^2 + 201d^2 + 10d^2}{0.1470d^2 \times 2{,}310d}$ (stray losses = about 1 per cent of P_2)

$= \frac{3.56}{d}$ (approximation, error < 10 per cent)

Summary

Weight of charge $W = 0.236d^3$
Power input $P = 1{,}201d^2$
Efficiency $E = 83.3$ per cent
Primary amp. turns $NI_1 = 2{,}310d$
Volts per turn $E_1/N = 0.1470d^2$
Power factor $PF = 3.56d^{-1}$

Hence, for a 2-ton furnace

$$d = \sqrt[3]{\frac{4{,}000}{0.236}} = 25.63 \text{ in.}$$

$$\text{Power input} = 1{,}201 \times 25.63^2 = 788 \text{ kw}$$

$$\text{Volts per turn} = 0.1470 \times 25.63^2 = 96.6$$

$$\text{Turns (for 1,000 volts)} = \frac{1{,}000}{96.6} = 10.36 \text{ or } 11.$$

$$\text{Current} = \frac{2{,}310 \times 25.63}{11} = 5{,}380 \text{ amp}$$

$$\text{Power factor} = \frac{3.56}{25.63} = 0.1388$$

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(Courtesy of Ajax Electrothermic Corporation, Trenton, N. J.)

[**Editor's Note.**—Lack of time precluded the reconstruction of this reference list in the complete and convenient form adopted as standard for Electrical Engineering. Therefore, the list is reproduced as supplied by the authors.]

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Control of Distance Relay Potential Connections

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By means of the automatic switching of potential connections to distance relays according to type of fault, each distance relay may be made to do the work of 2 or 3 such relays. The cost of distance relay installations may be reduced considerably by this automatic control of potential connections, and consequently their use should become more widespread.

DURING the past 5 years distance relays gradually have become more popular for the protection of important transmission lines on account of their rapid action and their immunity from the effects of variations of system set-ups and generating conditions. Their application, however, has been confined hitherto almost exclusively to networks above 110 kv and protection against faults involving more than one phase. Since financial outlay is the main reason for not extending their application further it is the purpose of this paper to show how more and better protection can be obtained per dollar's worth of distance relay.

In Continental Europe, distance relays have enjoyed a much wider popularity than in this country although the relays used there are, in general, slower. Automatic potential switching has had a good deal to do with their wide application. One distance relay is made to do the work of 2 or 3 by automatically providing it with potential from the proper phase upon the occurrence of a fault.

While this subject therefore is not entirely new, it has not previously appeared in publications in this country, as far as the author is aware. The schemes described are mostly based upon European practice modified where necessary for use with modern American high speed distance relays. They are suitable for either impedance or reactance relays except where mentioned.

Conclusions which may be drawn from the methods described in this paper are that with automatic potential switching the application of distance relays can be extended as follows:

1. The expense of a complete set of distance relays on lines of secondary importance can be avoided by making one distance relay protect all 3 phases against interphase faults (Figs. 1 and 2).
2. On certain lines one distance relay can be made to protect a 3-phase line against ground faults (Fig. 3).
3. Three distance relays can be made to protect against ground faults in addition to interphase faults (Figs. 8 and 9).
4. With lessened accuracy and rather complicated switching a single distance relay can be made to provide protection against interphase and ground faults (Fig. 7).

In each scheme auxiliary relays (referred to as selector relays) are provided which are associated with individual phases or with the residual circuit. The potential circuits of the distance relays are connected to the appropriate phases of the secondary potential supply by the selector relays according to which phases are involved in the fault. This may be done either directly through contacts on the selector relays (as in Figs. 1, 2, 3, 4, 7, 9, and 10) or indirectly through contacts on d-c auxiliary relays, called a transfer relay (as in Figs. 5 and 8).

Where the fault current always exceeds the load current, the selector relays can be simple instantaneous overcurrent relays, as indicated in Figs. 1–4, 7, and 10 and can sometimes be mounted within the distance relay itself. In the less frequent cases where operation is desired on faults with less than normal current, voltage restraint coils can be added to prevent them from picking up under normal conditions (see Figs. 5, 8, and 9).

ONE DISTANCE RELAY FOR INTERPHASE FAULTS

In Fig. 1 is shown a Continental arrangement, using one distance relay instead of 3 for faults between phases. In order to prevent operation normally while the potential circuit of the distance relay is short-circuited, it should have a starting unit which cannot operate on current alone. Table I shows how the distance relay is energized for faults between the various phases. It will be noticed that a fault between phases 1 and 2 or a 3-phase fault provides current from both the current transformers, but the distance measurement is kept the same by bypassing half the current through the "impedor" Z.

In Fig. 2 and Table II is shown an alternative arrangement which avoids the special connection of the current transformers by means of double current windings on the distance relay. In this dia-

Table I—Methods of Energizing Distance Relay of Fig. 1

Fault	Potential	Current	Ohms
3-phase	E_{13}	$^1/_2(I_1 - I_3)$	$2X_p$
Phases 1-2	E_{12}	I_1	$2X_p$
Phases 2-3	E_{23}	$-I_3$	$2X_p$
Phases 3-1	E_{13}	$^1/_2(I_1 - I_3)$	$2X_p$

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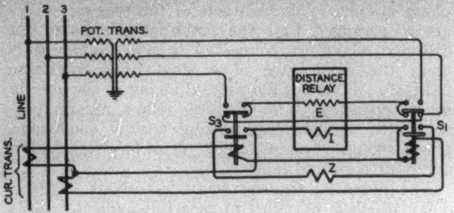

Fig. 1. One distance relay for phase-to-phase faults

S_1 and S_3. Selector relays
E and I. Potential and current windings of distance relay
Z. Impedance equal to that of current winding for equalizing the relay current during similar faults on different phases

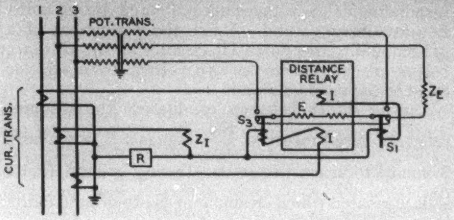

Fig. 2. One distance relay for phase-to-phase faults

S_1 and S_3. Selector relays
E and I. Potential and current windings of distance relays
R. Residual current circuit
Z_E. Impedance equal to that of E windings for equalizing the ohmic measurement
Z_I. Impedance equal to that of I windings for balancing current transformer burdens

gram also the impedor is in the potential circuit, thus eliminating the low resistance type of contacts necessary in Fig. 1 for short-circuiting the impedor in the current circuit. On the other hand, while the selector relays can be made more simply, the distance relay itself must be of superior design because it receives approximately double current and voltage for faults involving phases 1 and 3, and must still give the same distance measurement and operating time though influenced by 4 times the power.

The economy realized from the elimination of 2 relays out of each set enables distance relays to be used on lines whose importance does not warrant the expense of 3 distance relays per breaker, in spite of their superior protection and greater flexibility.

ONE DISTANCE RELAY FOR GROUND FAULTS

Similar but even simpler switching means can sometimes be used in the case of a ground distance relay (see Fig. 3). In this circuit the current coils are supplied with residual current and the potential coils with potential from phase 1 normally. Upon the occurrence of a fault in phases 2 or 3, the line current operates the corresponding switching relay to switch it to the proper phase-to-neutral potential.

It will be seen that during 2-phase faults the distance measurement will be inaccurate. The error will be on the high side with impedance relays so that back-up protection will be given to the interphase distance relays. Reactance relays will require an additional selector relay in the third phase with a contact arrangement similar to that of Figs. 5 and 8, to prevent action on faults involving more than one phase; otherwise, the phase angle on interphase faults could cause underestimation of the distance.

The reactance measured by a relay supplied with wye voltage and residual current during a single-phase-to-ground fault (see Appendix *B*) is $^1/_3 \left(X_o + \frac{A+B}{C} \times X_p\right)$ where A, B, and C are factors dependent upon magnitude and location of the generation and grounding points (see Appendix *A*) and X_o and X_p are respectively the zero phase sequence and positive phase sequence reactance between the relay and the fault.

Table II—Methods of Energizing Distance Relay of Fig. 2

Fault	Potential	Current	Ohms
3-Phase	E_{13}	$I_1 - I_3$	X_p
Phases 1-2	$^1/_2E_{12}$	I_1	X_p
Phases 2-3	$^1/_2E_{23}$	$-I_3$	X_p
Phases 3-1	E_{13}	$I_1 - I_3$	X_p

The distance measurement is therefore affected by change in system set-up and would only be constant on lines not subject to wide variations in system arrangement. However, the protection afforded to most lines would be better than that obtainable from the ordinary residual time-power relay.

THREE RELAYS FOR COMPLETE PROTECTION

In cases where 3 distance relays are already installed for protection against interphase faults, their duties can be extended to single-phase ground faults also by providing potential switching means as shown in Fig. 4.

The distance relays are supplied with wye current. Their potential circuits are connected to the cor-

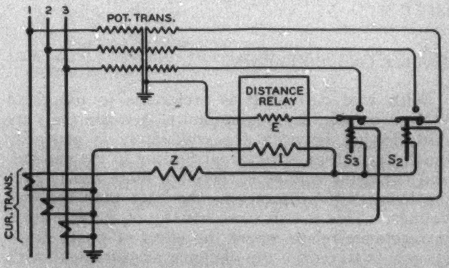

Fig. 3. One distance relay for phase-to-ground faults

S_2 and S_3. Selector relays
E and I. Potential and current
Z. Dummy impedance to balance current transformer burdens

responding delta voltages normally and during faults not involving ground. Upon the occurrence of a ground fault, the potential circuits of the distance relays are transferred to wye voltage by a selector relay in the residual circuit.

During faults between conductors the distance relay in phase 1 measures $\frac{E_{12}}{I_1}$ which is 2 X_p when only 2 conductors are involved. During ground faults $\frac{E_1}{I_1}$ is measured which on single-phase-to-ground faults is $X_p + \frac{X_o - X_p}{1+\frac{A+B}{C}}$. The impedances Z_1, Z_2, and Z_3 are provided for making the distance measurement as nearly as possible the same for phase faults and ground faults. Their value depends upon the value of A, B, and C for the particular line and can range from zero to the impedance of the potential circuit for one distance relay. These impedances would tend toward zero on lines with no ground wires. The distance measurement does not depend upon which phases are involved because the connections are symmetrical.

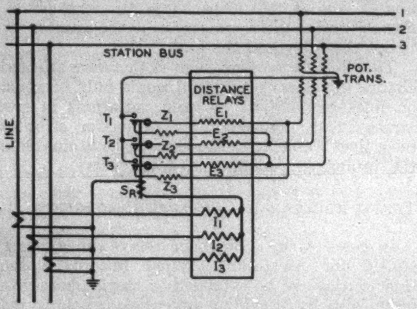

Fig. 4. Three distance relays for interphase ground faults

E_1, E_2, E_3. Potential circuits of distance relays
I_1, I_2, I_3. Current circuits of distance relays
S_r. Selector relay
T_1, T_2, T_3. Potential transfer contacts
Z_1, Z_2, Z_3. Equalizing impedances

Double Ground Faults

With wye current it is preferable to use delta voltage on double ground faults, because the current flowing between the conductors is generally much larger than the current flowing in the ground, and the delta voltage is therefore more nearly proportional to the distance to the fault than the wye voltage. This is still more worthy of consideration in reactance relays where the effect of phase angle is such as to reduce the distance measurement with wye voltage sometimes to zero on a double ground fault (see Fig. 6).

Accordingly in Fig. 5 the selector relay in the residual circuit is replaced by 3 selector relays in the phase circuits. The contacts of the selector relays are so arranged that the potential circuits of the distance relays are connected to wye voltage only upon the occurrence of a single-phase-to-ground fault, i. e., if one but not more than one of the selector relays operates. The distance relays remain connected to delta voltage during normal conditions, power swings, 3-phase faults, phase-to-phase faults, and double ground faults.

The potential transfer relay has about 0.04-sec. delay which is provided in case the 2 selector units do not operate simultaneously on a double ground fault, and permit the distance relay to be switched to wye voltage, which might cause low distance measurement, as just explained, since zero sequence compensation is not provided in the scheme.

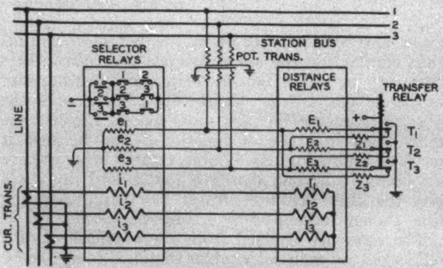

Fig. 5. Three distance relays for interphase and ground faults

E_1, E_2, E_3. Potential circuits for distance relays
I_1, I_2, I_3. Current windings of distance relays
T_1, T_2, T_3. Contacts of transfer relay
e_1, e_2, e_3. Potential windings of selector relays
i_1, i_2, i_3. Current windings of selector relays
1, 2, 3. Contacts of selector relays
Z_1, Z_2, Z_3. Equalizing impedances

It will be seen that the distance relays are allowed to operate immediately on all interphase faults. Upon the occurrence of a single-phase-to-ground fault the distance relay will not operate (unless the fault is close to the bus) until the potential has been switched from delta to wye. The tripping is held up in this case by the safety delay of 0.04 sec in the transfer relay; but this small delay in clearing single-phase-to-ground faults would not endanger stability and, therefore, would seldom be objectionable.

More accurate measurement of distance would be obtained if the distance relays were provided with wye voltage during 3-phase faults which would make it read the same distance as with delta voltage on phase-to-phase faults (if provided with equalizing impedances to halve the delta voltage on phase-to-phase faults). If the 3-phase fault were not balanced the relay in the most severely faulted phase would read substantially correctly, the other 2 higher.

Though employed later, this connection is not used in Fig. 5 because the latest type of distance relays would often operate before the transfer to wye voltage took place. The difference in distance measurement in the 2 types of faults would be 1 to

1.15 in the impedance relay and $\frac{1 \text{ to } 1.15 \sin \phi}{\sin (\phi + 30 \text{ deg})}$ in the reactance relay. The ratio is unity in the reactance relay on lines where ϕ is 60 deg and greater than unity for more-lagging lines. The ratio is less in both types of relays if the 3-phase fault is not exactly balanced.

The use of 3 impedance units as selector relays might give the impression that the total number of distance relays has not been reduced. These impedance units, however, are simply instantaneous overcurrent relays with voltage restraining coils to raise their pick-up at normal voltage while permitting them to operate on faults of less than normal current. They can be small and of the simplest construction since only an approximate impedance characteristic is required.

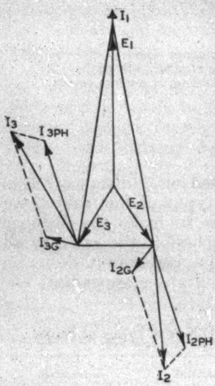

Fig. 6. Vector diagram showing that wye current and wye voltage will not allow a distance relay to measure correctly in a double-ground fault

E_1, E_2, E_3. Wye voltages
I_1, I_2, I_3. Wye currents
I_{ph}. Current flowing between conductors
I_g. Current flowing in ground

ONE DISTANCE RELAY FOR COMPLETE PROTECTION

The duties of the distance relays can be extended, of course, more and more, using auxiliary relays with suitably connected contacts, until the limit is reached when only one distance relay is used for protection against all phase and ground faults. Such an arrangement is shown in Fig. 7, which is based upon a circuit developed abroad.

The contacts *a*, *b*, *c*, and *d* of the selector relays are shown separately from their corresponding coils *A*, *B*, *C*, and *D* in order to simplify the diagram. Letters are used to indicate these relays, instead of the designation S_1, S_2, S_3 used elsewhere, because there are additional intermediate selector relays *F* and *G* and because a distinctive marking is necessary to locate quickly the coils and various contacts of each selector relay.

Table III—General Operation of Relay of Fig. 7

Fault	Selectors	Potential	Current
3-phase	D, B, C	$-KE_{31}$	$-\frac{1}{2}(I_3 - I_1)$
1-2	A, B	KE_{12}	I_1
2-3	B, C	KE_{23}	I_2
3-1	A, C	$-KE_{31}$	$-\frac{1}{2}(I_3 - I_1)$
1 to ground	A, D, F	E_1	I_1
2 to ground	B, D, F, G	E_2	I_2
3 to ground	C, D, F	$-E_3$	$-I_3$
1-2-ground	A, B, D	KE_{12}	I_1
2-3-ground	B, C, D, F	KE_{23}	I_2
3-1-ground	A, C, D, F	$-KE_{31}$	$-\frac{1}{2}(I_3 - I_1)$

The contacts *g* cut in the winding W_3 of the auxiliary current transformer only during single-phase faults between phase 2 and ground. The windings W_1 and W_2 are used for all other faults. Both windings are energized simultaneously only in the case of a fault between phases 1 and 3, but the impedance Z_4 bypasses enough current to keep the relay current the same as for a similar fault between one of the other pairs of phases. The compensating impedances in series with the potential transformer secondaries have to be adjusted to obtain the same distance measurement on phase-to-phase faults as on single-phase-to-ground faults.

The economy of making one distance relay do the work of 6 is acheived somewhat at the expense of performance. The distance relay must not be allowed to trip until all the selector relays have operated that should operate; and, in order to be sure of this, the selector relays must be more rapid than the distance relay over the range of current expected, or the distance relay must be suitably delayed. Furthermore, the continuity of the potential circuit depends upon the perfect operation of the several contacts in series with it.

The ohmic measurement varies somewhat for different types of faults, and for this reason could not be applied to important lines. For instance, for faults involving phase 2 a certain amount of current may be supplied from phases 1 and 3 if some of the fault current returns along those conductors. The general operation is as shown in Table III.

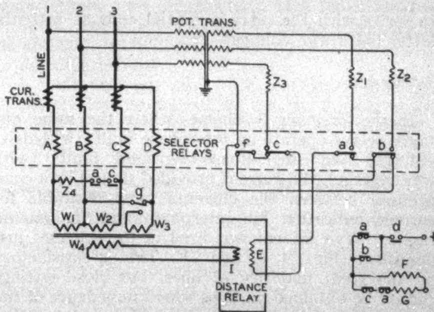

Fig. 7. One distance relay for phase-to-phase and phase-to-ground faults

A, B, C, D. Selector relay coils
a, b, c, d. Selector relay contacts
G, F and g, f. Auxiliary relay coils and contacts
W_1, W_2, W_3, W_4. Windings of auxiliary current transformer
Z_4. Impedance for halving current in W_1 and W_3
Z_1, Z_2, Z_3. Impedances for equalizing measurement of distance relay on phase and ground faults

The factor *K* is less than unity and is introduced by the equalizing impedances Z_1, Z_2, Z_3 in order to make the distance measurement on interphase faults as nearly as possible the same as that on single-phase-to-ground faults. With the former (with delta voltage) there is twice the impedance

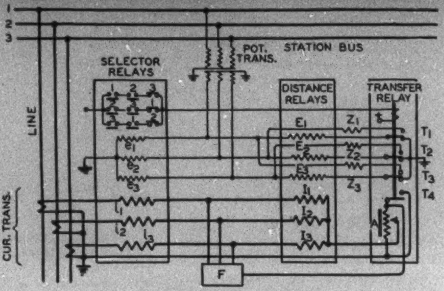

Fig. 8. Zero sequence current compensation with one current switch

E_1, E_2, E_3. Potential circuits for distance relays
I_1, I_2, I_3. Current windings of distance relays
T_1, T_2, T_3, T_4. Contacts of transfer relay
T_4 is a vacuum contact in the current circuit
F. Zero sequence current filter
e_1, e_2, e_3. Potential windings of selector relays
i_1, i_2, i_3. Current windings of selector relays
1, 2, 3. Contacts of selector relays
A. Tapped auto current transformer for adjusting ratio of residual to phase current
Z_1, Z_2, Z_3. Equalizing impedances

in series with the relay potential coils as with the latter (with wye voltage).

ACCURACY

In the foregoing 3 schemes where the same distance relays operate on interphase faults (with delta voltage) and single-phase-to-ground faults (with wye voltage), the current provided should be a compromise between the currents most desirable for correct indication for interphase and for ground faults. Wye current was used in the schemes just described (Figs. 4, 5, and 7). This is satisfactory on the great majority of lines, but close settings cannot be obtained on lines where impedance of the ground circuit varies considerably with system connections (see Appendix *A*).

However, in the few cases where it is necessary to limit the instantaneous zone of the distance relays to only 50 per cent of the protected section on single-phase-to-ground faults, the protection secured will still be better than that afforded by inverse time-current or time-power relays supplied from the residual circuit.

On lines of primary importance if the system set-up is liable to be considerably varied to meet load conditions it is evident that the use of one distance relay for complete protection is not flexible enough for accurate distance measurement without making the circuit still more complicated. With 3 distance relays, however, the switching circuit is easier to handle because it is symmetrical. Each distance relay protects one phase in exactly the same manner as the 2 in the other 2 phases and any desired compensating feature can be added directly by means of contacts on the transfer relay which switches the 3 distance relays simultaneously and similarly.

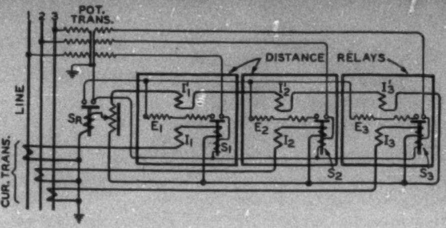

Fig. 9. Zero sequence current compensation without current switching

S_1, S_2, S_3. Phase selector relays
S_r. Residual selector relay
E_1, E_2, E_3. Potential circuits of distance relays
I_1, I_2, I_3. Phase current windings of distance relays
I_1', I_2', I_3'. Residual current windings of distance relays

CONNECTIONS REQUIRED

Having tentatively decided on 3 distance relays for protection against all types of line faults, we shall see what can be done to make the distance measurement as nearly as possible the same in all cases. Table IV shows the connection desirable for the different types of faults (see appendix).

Table IV—Connections for Different Types of Faults

Type of Fault	Suitable Connections	Alternatives
3-phase	$\frac{E_{delta}}{I_{delta}}$	$\frac{E_{wye}}{I_{wye}}$
Phase-to-phase	$\frac{E_{delta}}{I_{delta}}$	$\frac{E_{delta}}{I_{wye}}$
Double ground	$\frac{E_{delta}}{I_{delta}}$	$\frac{E_{wye}}{I_{wye} + KI_{residual}}$
		$\frac{E_{delta}}{I_{wye} - {}^1/_3 I_{residual}}$
Single ground	$\frac{E_{wye}}{I_{wye} + KI_{residual}}$	

Since delta current is not desirable in single-phase-to-ground faults the use of it would involve switching in the current circuits. This presents more difficulty than in potential circuits because: (1) the amount of current, and therefore the contact duty, is more severe; (2) low resistance contacts must be maintained in order to avoid heating and imposing extra current burden; (3) the current transformers must never be open-circuited; and (4) the switching must be completed in a fraction of a cycle. Vacuum switches are now available for meeting these requirements but at present a group such as would be needed would be bulky and expensive and require appreciable force to operate. Consequently, we shall decide on wye current for interphase faults. The residual current required for ground faults can be controlled without transfer switches, as shown in Figs. 8 and 9. The potential connections are now fixed by the choice of wye current.

COMPLETE PROTECTION WITH CURRENT COMPENSATION

The connections of Fig. 8 are similar to those of Fig. 7 except that the circuit is modified in accordance with the table of connections (Table IV), required for greatest accuracy. Delta voltage is used for double ground faults in order to avoid the use of an extra selector relay in the residual circuit for distinguishing between double-ground and phase-to-phase faults. The current circuit is so arranged that while residual is added in the relay coils during single-phase-to-ground faults it is removed during double-ground faults leaving the relay with only the positive and negative sequence components of voltage and current.

The contacts in the potential and current circuits are operated together. The figure shows the contacts as they would be for normal conditions, power swings, 3-phase faults, and single-phase-to-ground faults; the distance relay potential circuits have the phase-to-neutral voltages and their current circuits have wye current plus the proper proportion of the residual current (in single-phase-to-ground faults).

Only upon the occurrence of a phase-to-phase or a double-ground fault is the transfer relay permitted by the selector relays to pick up. The distance relay potential circuits are then switched from wye to delta voltage and the zero sequence current is bypassed (in the case of double-ground faults) through the zero sequence filter which is of low impedance compared with the alternative path through the relays and the autotransformer.

As an alternative the current contacts on the transfer relay could have been eliminated by providing a selector relay in the residual circuit with its contacts in parallel with the group of contacts of the existing selector relays. In this way, during a double-ground fault the relay would receive E_{wye} and $I_{wye} + KI_{residual}$.

Instantaneous operation is obtained on 3-phase faults (where the risk of instability is a maximum) and single-phase-to-ground faults, while the small delay of the selector relay occurs only on 2-phase faults. This is preferable on some systems wehre prompt removal of a single-phase fault to ground may prevent the arc from spreading to a second phase.

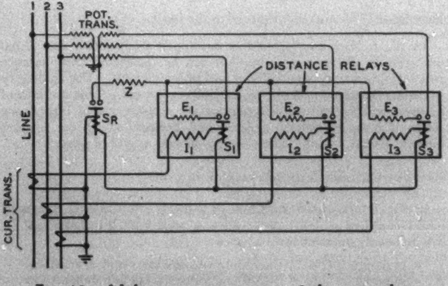

Fig. 10. Voltage compensation in 3 distance relays

S_1, S_2, S_3. Phase selector relays
S_r. Residual selector relay
E_1, E_2, E_3. Potential circuits of distance relays
I_1, I_2, I_3. Phase current windings of distance relays

ZERO SEQUENCE COMPENSATION WITHOUT CURRENT SWITCHING

In Fig. 9, which is based upon a European circuit, the switching contacts are reduced to a minimum and the connections are simple. One distance relay is used per phase for all types of faults. Each distance relay contains a small instantaneous overcurrent or impedance selector unit which connects one end of the potential circuit to the corresponding phase of the secondary potential bus when that phase of the protected line becomes involved in a fault. The other ends of the potential circuits of the distance relays are connected together to form a star point. This point is connected to the neutral of the secondary potential bus if the fault is to ground.

The current circuits of the distance relays have double windings. One winding is supplied with current from the same phase as the potential and the other is connected to a tapped auxiliary current transformer in the neutral circuit of the line current transformers. By means of the taps the amount of residual current supplied to the distance relays can be adjusted according to the ratio of X_z to X_p as explained previously.

A fault between any 2 phases causes 2 of the distance relays to receive the current flowing in the affected phases and half the voltage between them, i. e., $\frac{1/_2\, E_{delta}}{I_{wye}}$, which is X_p. In a 3-phase fault the distance relays receive wye current and the corresponding wye voltage, i. e., $\frac{E_{wye}}{I_{wye}}$, which is also X_p.

When one phase has a fault to earth the residual overcurrent relay picks up so that the corresponding distance relay receives the wye voltage of that phase. The 2 current coils of the relay are energized with the phase current and residual current respectively so that the ohmic indication is $\frac{E_{wye}}{I_{wye} + KI_{residual}}$ which is also X_p.

In a double ground fault the residual relay causes the 2 affected distance relays to have wye potential

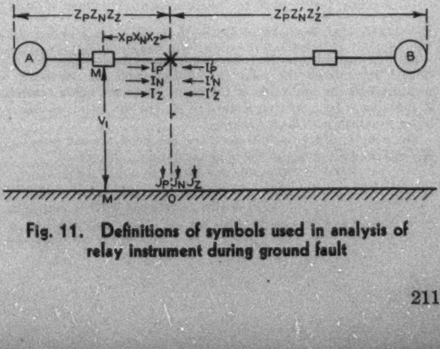

Fig. 11. Definitions of symbols used in analysis of relay instrument during ground fault

while their current circuits have phase plus residual current so that the distance measured is $\frac{E_{wye}}{I_{wye} + KI_{residual}}$ which is again X_p.

This arrangement is the cheapest for complete line protection with accurate distance measurement. The distance relay operation is delayed by the small period taken by the selector relays to operate. This is the same for any type of fault.

In order that the distance relays may not operate normally when their potential circuits are deënergized, they must be controlled by a directional starting unit or else back contacts must be provided on the initiating relays to deënergize the operating current coils of the distance relays.

In very many cases the variations in system set-up do not affect the distance measurement on ground faults sufficiently to warrant zero sequence compensation. On the majority of lines it is sufficient to provide partial compensation by putting an impedance in series with the neutral of the distance relay potential circuits as shown in Fig. 10. This impedance can be a resistor in the case of relays having potential circuits which are of unity power factor or which can be made unity power factor by a parallel condenser. Its magnitude is such as to cause the relay to measure the same distance on single-phase-to-ground faults as with balanced 3-phase faults, i. e., to reduce the voltage on single-phase-to-ground faults in the same proportion as the current when the residual compensation is omitted.

Appendix A

IMPEDANCE OF LINE-TO-GROUND FAULTS

In a fault between phases the voltage between the faulty pair of conductors divided by the current flowing in them gives an impedance which is proportional to the distance from the fault because only the positive and negative phase sequence components are involved and they depend only upon the length of the line.

In a ground fault however this impedance is not always proportional to the distance from the fault on account of the fact that zero phase sequence component is included which is affected by changes in the location of the system grounding points, the mutual effect of the current returning in the ground and the other 2 conductors, which means that changes in generation and system connections will have an effect upon the value of $\frac{E}{I}$.

COMPENSATION FOR THE EFFECT OF MUTUAL INDUCTANCE OF RETURN CURRENTS

With phase 1 grounded the phase-to-neutral voltage E_1 will be

$$E_1 = 1/3(I_1 + aI_2 + a^2I_3)X_p + (I_1 + a^2I_2 + aI_3)X_n + (I_1 + I_2 + I_3)X_z$$

where the currents are those flowing towards the fault in one direction, i. e., through the relay in question, and the reactances are measured on the same side of the fault, resistance being neglected. Z could have been written instead of X, but the latter was used in order to match with later equations.

Since $X_p = X_n$ for points along the line itself, we can put $X_p = X_n = X$ and $X_z = K_X$ in the above equation. Therefore

$$E = \frac{1}{3}\left[\{2I_1 + (a^2 + a)I_2 + (a + a^2)I_3\}X + (I_1 + I_2 + I_3)KX\right]$$

$$= \frac{X}{3}\{2I_1 - I_2 - I_3 + K(I_1 + I_2 + I_3)\}$$

$$= \frac{X}{3}\{3I_1 + (I_1 + I_2 + I_3)(K - 1)\}$$

$$= X\left\{I_1 + I_r \times \frac{K-1}{3}\right\}$$

A distance relay for ground fault protection using wye voltage and the wye current in the same phase can therefore be set to operate on X_p (which is a direct measure of the length of line involved) if a component of the residual current be added to the line current in the current coils, in order to give correct operation under all ground fault conditions.

The relay in phase 1, in order to give a true indication of the proximity of the fault, must therefore measure $X = \frac{E_1}{I_1 + \frac{(K-1)I_r}{3}}$ where I_r is the residual current of the 3 current transformers and where $K = \frac{X_z}{X_p}$.

SETTING THE VALUE OF K

The amount of residual current which should be added to the phase current to compensate for the variations just discussed depends upon the ratio of the zero phase sequence reactance to the positive phase sequence reactance of the protected line, i. e., $K' = \frac{K-1}{3}$. Table V shows approximately how K' would vary with copper and steel ground wires and with no ground wires.

Table V—Values of K′

No. of Ground Wires	Kind of Wire	I_s in Ground Wire	I_s in Ground	$K = \frac{X_z}{X_p}$	$K' = \frac{K-1}{3}$
0		0%	100%	3.5 –4	0.83 to 1.0
1	Steel	5%	95%	3.5 –4	0.83 to 1.0
1	Copper	40–50%	60–50%	2.75–3	0.57 to 0.67
2	Copper	50–70%	50–30%	2	0.33
Perfect return path		100%		1	0

It is not always necessary to compensate for variations due to system set-ups. For instance it will be seen from the above tests that in some lines only $^1/_3$ of the residual current need be added to the phase current for full compensation. This does not mean that the variations in distance measurements will be 33 per cent without compensation because some of the departure from X_p is fixed and can be taken up by changing the distance setting on ground faults, which is easy if the relay setting is made by adjusting the potential circuit.

On some lines the location of grounding points is never changed and the layout of the system is such that the location of the fault does not appreciably affect the relation between the line-to-ground impedance $\frac{E_{wye}}{I_{phase}}$ and the distance to the fault.

In the following a formula is developed from which the actual variation in distance measurement can be calculated in a distance relay supplied with wye voltage and phase current. For simplicity impedances are considered instead of reactances. This method of analysis was taken from "Report on the Application of Impedance Relays for the Protection of Overhead Transmission Lines Against Ground Faults," by J. Fallou (see references at end of paper).

EFFECT OF CHANGES IN SYSTEM CONNECTIONS

In Fig. 11 is shown a section of 3-phase transmission line with power supplied at both ends and a ground fault on phase 1 at O. The following notations will be used:

Z = impedance O to A (including transformers and generators)
Z' = impedance O to B (including transformers and generators)
X = impedance O to M (The symbol X is used instead of Z to avoid confusion with the other Z terms)
$\underline{Z}$ = total impedance from fault to ends of line including both sets of transformers and generators, so that $\frac{1}{\underline{Z}} = \frac{1}{Z} + \frac{1}{Z}$

Similarly the total current in fault $J = I + I'$ flowing from A and B, respectively, in the lines shown in Fig. 11.

Also in phase 1 the total short-circuit current at O is

$$J_1 = J_p + J_n + J_s$$

also

$$J_p = J_n = J_s = \frac{E}{\underline{Z}_p + \underline{Z}_n + \underline{Z}_s}$$

where E is the Y voltage.

Since $\frac{1}{\underline{Z}_p} = \frac{1}{Z_p} + \frac{1}{Z_p'}$, and the same for the other components

$$I = \frac{\underline{\underline{Z}}_p}{Z_p} Jp, \quad I_n = \frac{\underline{\underline{Z}}_n}{Z_n} \times J_n, \quad \text{and } I_s = \frac{\underline{\underline{Z}}_s}{Z_s} \times J_s, \text{ therefore}$$

$$I_1 = I_p + I_n + I_s = \frac{E}{\underline{Z}_p + \underline{Z}_n + \underline{Z}_s} \left\{ \frac{\underline{\underline{Z}}_p}{Z_p} + \frac{\underline{\underline{Z}}_n}{Z_n} + \frac{\underline{\underline{Z}}_s}{Z_s} \right\}$$

The star voltage V_1 at the relay M has components X_pI_p, X_nI_n, X_sI_s and its value is therefore

$$E_1 = \frac{E}{\underline{Z}_p + \underline{Z}_n + \underline{Z}_s} \left\{ X_p \frac{\underline{\underline{Z}}_p}{Z_p} + X_n \frac{\underline{\underline{Z}}_n}{Z_n} + X_s \frac{\underline{\underline{Z}}_s}{Z_s} \right\}$$

since voltage drops are produced only by components of current reacting with like components of impedance.

Then dividing by the expression for I_1 we have

$$\frac{E_1}{I_1} = \frac{X_p \cdot \frac{\underline{\underline{Z}}_p}{Z_p} + X_n \times \frac{\underline{\underline{Z}}_n}{Z_n} + X_s \cdot \frac{\underline{\underline{Z}}_s}{Z_s}}{\frac{\underline{\underline{Z}}_p}{Z_n} + \frac{\underline{\underline{Z}}_n}{Z_p} + \frac{\underline{\underline{Z}}_s}{Z_s}}$$

Let us make $\frac{\underline{\underline{Z}}_p}{Z_p} = A$; $\frac{\underline{\underline{Z}}_n}{Z_n} = B$; and $\frac{\underline{\underline{Z}}_s}{Z_s} = C$

Therefore

$$\frac{E_1}{I_1} = \frac{X_pA + X_nB + X_sC}{A + B + C}$$

$$= \frac{X_p(A + B) + X_sC}{A + B + C}, \text{ because } X_p = X_n \text{ for a transmission line}$$

$$= \frac{X_p(A + B + C) + (X_s - X_p)C}{A + B + C}$$

$$= X_p + \frac{X_s - X_p}{\frac{A + B + C}{C}}$$

$$= X_p + \frac{X_s - X_p}{1 + \frac{A + B}{C}}$$

$$= X_p + \frac{X_s - X_p}{\frac{1 + \frac{\underline{\underline{Z}}_p}{Z_p} + \frac{\underline{\underline{Z}}_n}{Z_n}}{\frac{\underline{\underline{Z}}_s}{Z_s}}}$$

In his previously mentioned article, Jean Fallou also works out an expression for the distance measurement of an uncompensated distance relay during double-ground faults. The expression is somewhat complicated and the reader is referred to the article for the analysis.

Variations in distance measurement during double-ground faults can be avoided by zero sequence compensation or by connecting the relay so as to consider a double-ground fault the same as a phase-to-phase fault, i. e., by eliminating the zero sequence components from both the potential and current circuits, either by using delta voltage and delta current or by using delta voltage and eliminating the zero sequence components from the wye current by means of a filter or a 4-winding transformer.

DISTANCE MEASUREMENT WITH ZERO SEQUENCE COMPENSATION

It can be shown quickly that by adding the proper amount of residual current the distance measurement depends only on the positive sequence reactance between the relay and the fault.

$$I_{ph} = I_p + I_n + I_s = \frac{E}{\underline{Z}_p + \underline{Z}_n + \underline{Z}_s}(A + B + C)$$

$$I_r = 3I_s = \frac{3E}{\underline{Z}_p + \underline{Z}_n + \underline{Z}_s} \cdot C$$

$$E_{ph} = \frac{E}{\underline{Z}_p + \underline{Z}_n + \underline{Z}_s}(AX_p + BX_n + CX_s)$$

Combining the above identities, we have

$$\frac{E_{ph}}{I_{ph} + \frac{K - 1}{3} \cdot I_r} = \frac{X_pA + X_nB + X_sC}{A + B + C + (K - 1)C}$$

$$= \frac{X_p(A + B) + X_sC}{A + B + KC} \text{ (assuming } X_p = X_n \text{ for a transmission line)}$$

$$= \frac{X_p(A + B + KC) + (X_s - KX_p)C}{A + B + KC}$$

$$= X_p + \frac{X_s - KX_p}{A + B + KC}$$

Since $K = \frac{X_s}{X_p}$ the second fraction will always be zero and the relay indication $\frac{E_{ph}}{I_{ph} - \frac{K - 1}{3} I_r} = X_p$ which is proportional to distance and not affected by variations in A, B, and C.

Appendix B

In Fig. 3 wye voltage was used with residual current. On single-phase-to-ground faults the distance measurement with this combination would be as follows:

$$E_{wye} = \frac{E}{\underline{Z}_p + \underline{Z}_n + \underline{Z}_s} \cdot \{AX_p + BX_n + CX_s\}$$

$$I_r = \frac{3E}{\underline{Z}_p + \underline{Z}_n + \underline{Z}_s} \cdot C$$

Therefore

$$\frac{E_{wye}}{I_{residual}} = \frac{AX_p + BX_n + CX_s}{3C}$$

$$= {}^1/_3 \left\{ X_s + \frac{A + B}{C} \cdot X_p \right\}$$

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Auditory Perspective —Transmission Lines

This paper continued from p. 32. The sixth and final paper in this symposium entitled "Auditory Perspective—System Adaptation" follows the remainder of this paper, beginning on p. 216.

stantially flat within a fraction of a decibel from 40 cps to 15,000 cps. The lower curves indicate successively what happens if the phase angle of the receiving carrier is adjusted different amounts from the optimum adjustment. It may be noted that for a 90-deg departure the transmission of a 40-cycle tone over the carrier channel would suffer more than 12 db in comparison with a 1,000-cycle tone.

REPEATERS

As noted previously, the line circuit between Philadelphia and Washington included 5 intermediate repeater points. A schematic drawing of the apparatus installed at each point is shown in Fig. 8. The amplifiers at these points, as well as those used at the transmitting and receiving terminal, consisted of a new form of amplifier employing the principle of negative feed-back. The principal virtues of amplifiers of tihs type are their remarkable stability with battery and tube variations and great freedom from nonlinearity or modulation effects. Each amplifier is supplemented at its input by an equalizer designed to have its attenuation approximately complementary in loss to that of the line circuit in a single section. The amplifiers actually employed for the purpose were taken from a trial of a cable carrier system described in a recent A.I.E.E. paper by A. B. Clark and B. W. Kendall.[4]

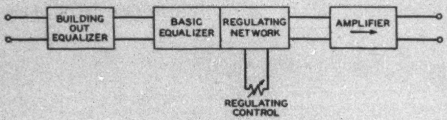

Fig. 8. Schematic diagram of repeater station apparatus

The losses in the cable circuits do not, of course, remain absolutely constant with time, and slow variations due to change of temperature are compensated for by occasional adjustments of the variable equalizer arrangements provided. These adjustments were required only infrequently; approximately at weekly intervals because in an underground cable the temperature experiences only slow, seasonal variations.

As noted, new repeater stations were established at 2 points. The housing arrangements for one of these points, Abingdon, is shown in Fig. 9. The equipment at this repeater point also included relays remotely controlled from the nearest attended repeater station to permit the repeaters to be turned on and off at will and the power supply, which consisted of storage batteries, to be switched from the regular to the reserve battery or either battery put on charge if required.

OVER-ALL PERFORMANCE

While the system was set up specifically to provide transmission for the demonstration into Washington on April 27, 1933, it was operated over a period of several weeks and complete tests and measurements were carried out for the purpose of gathering information on cable carrier systems. The complete layout of apparatus and lines provided between Philadelphia and Washington is shown in Fig. 10.

The over-all frequency transmission characteristics of the 3 channels that were set up are shown in Fig. 11. These curves differ from those shown in Fig. 7, and include the complete high frequency line circuit with its 150 miles of cable, repeaters, equalizers, and other equipment. It may be seen that between the desired frequency limits the circuit is substantially flat in transmission performance to within ±1 db. Various noise measurements made on the over-all circuit indicated that the circuits fully met the requirements that had been set up, and that the line and apparatus noise was inaudible in the auditorium at Washington even during the weakest music passages. The circuit also was found to be free from nonlinear distortion to a satisfactory degree. Harmonic components generated when single-frequency tones were applied to the channels at high volumes were found with one unimportant exception to be more than 40 db below the fundamental.

As a means of obtaining a further increase in volume range, which was not actually required for this demonstration, tests were made with a so-called predistortion-restoring technique. In this the higher frequency components of the music were transmitted over the carrier channels at a volume much higher than normal in relation to the volume of the lower frequencies. By this means any noise entering the carrier channels at frequencies equivalent to the higher music frequencies is greatly minimized in effect.

Fig. 9. Interior and exterior of special intermediate repeater station at Abingdon, Md.

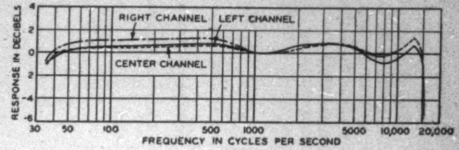

Fig. 11 (right). Frequency characteristics over carrier channels used between Philadelphia and Washington, D. C.

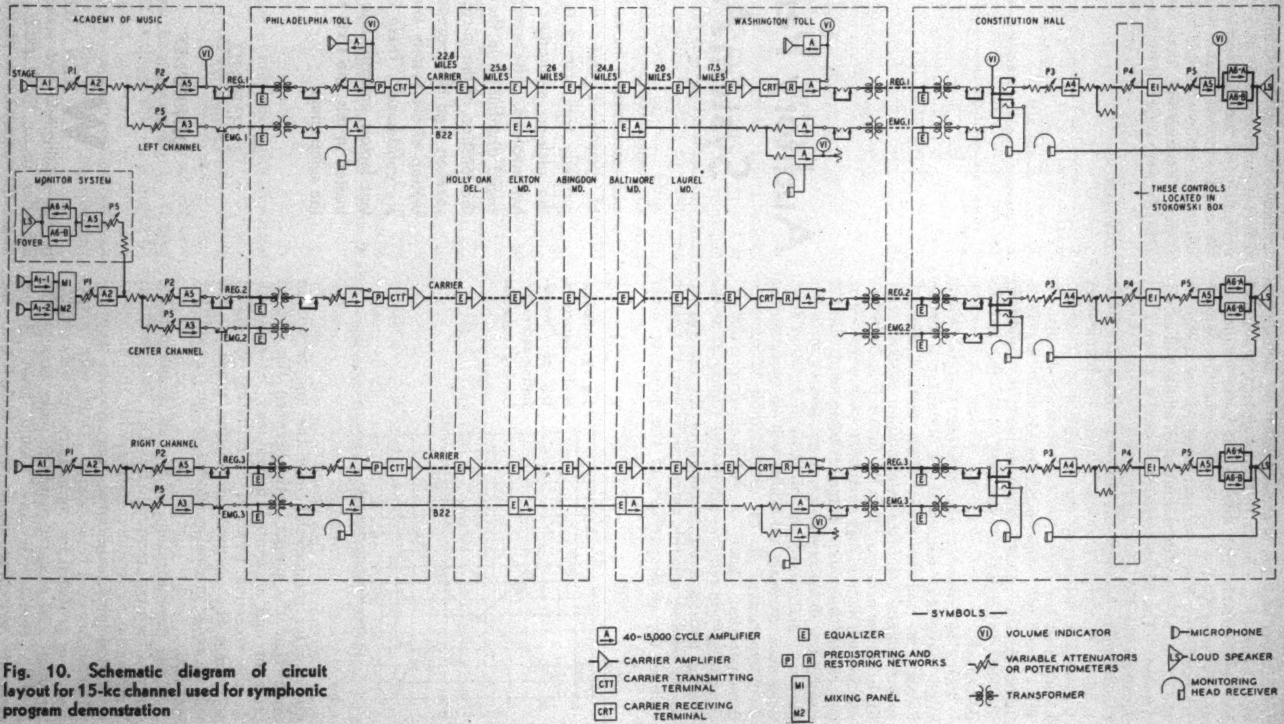
ACADEMY OF MUSIC
PHILADELPHIA TOLL
WASHINGTON TOLL
CONSTITUTION HALL
STAGE
LEFT CHANNEL
CENTER CHANNEL
RIGHT CHANNEL
MONITOR SYSTEM
FOYER
REG.1
EMG.1
REG.2
EMG.2
REG.3
EMG.3
CARRIER
B22
22.8 MILES
25.8 MILES
26 MILES
24.8 MILES
20 MILES
17.5 MILES
HOLLY OAK DEL.
ELKTON MD.
ABINGDON MD.
BALTIMORE MD.
LAUREL MD.
THESE CONTROLS LOCATED IN STOKOWSKI BOX
— SYMBOLS —
40-15,000 CYCLE AMPLIFIER
CARRIER AMPLIFIER
CARRIER TRANSMITTING TERMINAL
CARRIER RECEIVING TERMINAL
EQUALIZER
PREDISTORTING AND RESTORING NETWORKS
MIXING PANEL
VOLUME INDICATOR
VARIABLE ATTENUATORS OR POTENTIOMETERS
TRANSFORMER
MICROPHONE
LOUD SPEAKER
MONITORING HEAD RECEIVER

Fig. 10. Schematic diagram of circuit layout for 15-kc channel used for symphonic program demonstration

This predistortion is accomplished by including in the circuit at the input to the modulator a network having relatively high loss for the lower frequencies and tapering to low loss for the higher frequencies. Its maximum loss is compensated for by adding in the circuit an equivalent amount of additional amplification. The characteristics of such a network are illustrated in Fig. 12. To restore the normal volume relationships between the different tones and overtones a restoring network having complementary transmission frequency characteristics is, of course, included at the output of the receiving circuit. It was found with this predistortion-restoring technique that a volume range increase of something like 10 db could be obtained over the circuits described.

There is available also another method which might have been employed for obtaining a further increase in volume range. This method, the so-called volume compression-expansion system, very likely will be necessary if in the future it is desired to obtain such high quality circuits on long routes where the carrier frequency range is being used also for regular telephone message transmission or for other purposes, and where the problem of freedom from noise and crosstalk no doubt will be more serious than experienced in the Philadelphia-Washington demonstration. Such a volume compression-expansion system requires additional apparatus at the sending and receiving terminals of the line circuit. At the sending end this apparatus is used to raise in volume the weak passages of the music or other program for transmission over the line circuits in order that the proper ratio between the desired program and unwanted noises may be retained. At the receiving terminal coördinating apparatus reëxpands the compressed volume range to the volume range originally applied to the transmitting terminal.

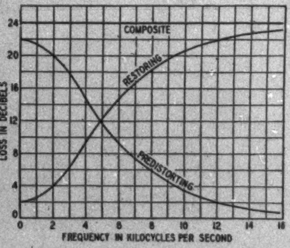

Fig. 12. Attenuation characteristics of "predistorting and restoring" networks

In the demonstration, to provide supplementary control features required by Dr. Stokowski at Washington for communicating with the orchestra at Philadelphia, additional wire circuits were established between these points. Order wire circuits also were provided for communication between the terminals and repeater points to make possible the location troubles if any should arise. Rather elaborate switching means were included at the terminals to permit switching the carrier channels to different microphones and to different amplifier equipment at the loud speaker end. To take care of the contingency of a cable pair failure, spare pairs of wires were made available to be switched in at short notice. Fortunately, none of the reserve facilities actually were required for the demonstration.

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Auditory Perspective —System Adaptation

A communication system for the pick-up and reproduction in auditory perspective of symphonic music must be designed properly with respect to the acoustics of the pick-up auditorium and the concert hall involved. The reverberation times and sound distribution in the two auditoriums, the location of the microphones and loud speakers, and the response-frequency calibration of the system and its equalization are considered. These and other important factors entering into the problem are treated in this, the sixth and final paper of the symposium.

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WHEN THE EFFECT of music or the intelligibility of speech is spoiled by bad acoustics in an auditorium, the audience is well aware that acoustics do play a most important part in the appreciation of the program. One may not be conscious of this fact when the acoustical conditions are good, but a simple illustration will show that the effect still is present. Thus, of the sound energy reaching a member of the audience as much as 90 per cent may have been reflected one or more times from the various surfaces of the room, and only 10 per cent received directly from the source of the sound.

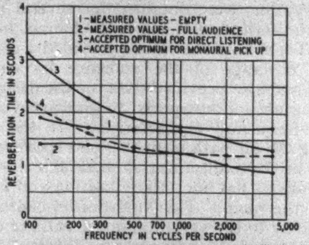

Fig. 1. Reverberation characteristics of Academy of Music, Philadelphia, Pa.

In listening to reproduced sound in an auditorium or concert hall, the effect of the room acoustics is perhaps even more important, for in this case the audience does not see any one on the stage and must rely entirely upon the auditory effect to create the illusion of the presence there of an individual or a group. Imperfections in the reproduced sound that are caused by defects in the acoustics of the auditorium may destroy the illusion and be ascribed improperly to the reproducing system itself.

In some types of reproduced sound, radio broadcast for example, where the reproduction normally takes place in a small room, the attempt is made to create the illusion that the listener is present at the source.[1,2] In the case considered here, however, where symphonic music is reproduced in a large auditorium, the ideal is to create the illusion that the orchestra is present in the auditorium with the audience. Since the orchestra is playing in one large room and the music is heard in another, the acoustical conditions prevailing in both must be considered.

PICK-UP CONDITIONS

The source room is the auditorium of the American Academy of Music in Philadelphia. This room has a volume of approximately 700,000 cu ft, and a seating capacity of 3,000. Measured reverberation time curves for this auditorium, and preferred values[3,4] for a room of this volume, are given in Fig. 1. It may be seen that with a full audience this room might be considered somewhat dead, but would be considered generally satisfactory for pick-up either with or without an audience. A floor plan of the Academy auditorium and stage, showing the location of the 3 microphones used, is given in Fig. 2. The microphone positions were selected after judgment tests using several locations and are much nearer the orchestra than they would be for single channel pick-up.[2] The use of the microphones near the orchestra results in picking up a high ratio of direct to reverberant sound and thus reduces the effect of reverberation in the source room upon the reproduced music. A high ratio of direct sound is desirable in the present case also because of the use of 3 channels. The perspective effect obtained with 3 channels depends to a considerable extent upon the relative loudness at the 3 microphones, and since the change in loudness with increasing distance from the source is marked for the direct sound only, and not for the reverberant, there would be a definite loss in perspective effect if the microphones were placed at a greater distance from the orchestra. This effect is discussed more fully in another paper of this symposium.

With the microphones located close to the orchestra their response-frequency characteristics will be essentially those given by the normal field calibration, since relatively little energy is received from the sides and back. For a distant microphone position it would be necessary to use the random incidence response characteristic, which differs from the normal because of the variation in directional selectivity of the microphones as the frequency varies. This difference in response characteristic depends upon the size of the microphone and may amount to as much as 10 db at 10,000 cps. It may be pointed out here that this difference in response is one factor frequently overlooked in the placement of microphones.

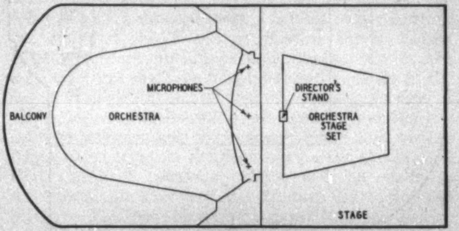

Fig. 2. Floor plan of Academy of Music, showing location of microphones

In addition to the 3 microphones regularly used, a fourth was provided to pick up the voice when a soloist accompanied the orchestra. In this case only the 2 side channels were used for the orchestra, the voice being transmitted and reproduced over the center channel. The solo microphone was so shielded by a directional baffle that it responded mainly to energy received from a rather small, solid angle. This arrangement permitted independent volume and quality control for the vocal and orchestral music.

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. winter convention, New York, N. Y., Jan. 23–26, 1934. Manuscript submitted Oct. 31, 1933; released for publication Dec. 4, 1933. *Not published in pamphlet form.*

THE CONCERT HALL

The music was reproduced before the audience in Constitution Hall in Washington, D. C. This hall has a volume of nearly 1,000,000 cu ft, and a seating capacity of about 4,000. A floor plan of the auditorium showing the location of the loud speakers and of the control equipment is given in Fig. 3. The loud speakers are placed so that each of the 3 sets radiates into a solid angle including as nearly as possible all the seats of the auditorium. Figure 4 shows the reverberation-frequency characteristics of Constitution Hall. The values given by the curve for the empty hall were measured through the use of the 3 regular loud speakers and several microphone positions in the room. The values for the hall with an audience present were calculated from known absorption data for an audience, and the optimum values are taken from accepted data for an auditorium of the volume of this one.[3] The reverberation times were considered satisfactory and no attempt was made to change them for this demonstration. The reverberation time measurements for both Constitution Hall and the Academy of Music were made with the high speed level recorder.[5] This instrument measures and plots on a moving paper chart a curve the ordinate of which is proportional to the logarithm of the electrical input furnished to it. When used in connection with a microphone for reverberation time measurements, curves are obtained showing the intensity of sound at the microphone during the period of sound decay. The rates of decay, and hence the reverberation times, are obtainable immediately from the slopes of these recorded curves and the speed of the paper chart.

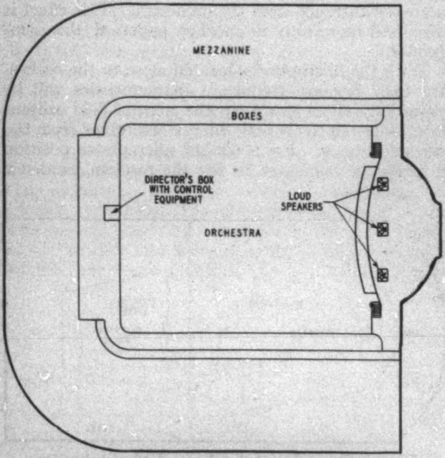

Fig. 3. Floor plan of Constitution Hall, Washington, D. C., showing locations of loud speakers

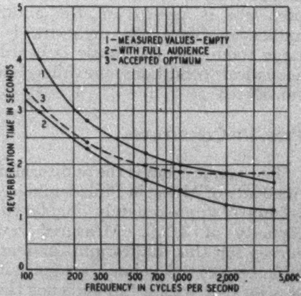

Fig. 4. Reverberation characteristics of Constitution Hall

CALIBRATION OF THE SYSTEM

In calibrating the system, a heterodyne oscillator connected to the loud speakers through the amplifiers was used. The oscillator was equipped with a motor drive to change the frequency, and as the frequency was varied through the range from 35 to 15,000 cps the sound was picked up with a microphone connected to the level recorder. Continuous curves of microphone response as a function of frequency thus were obtained for several positions in the auditorium, and for each channel independently. These response curves provided a check on a uniform coverage of the audience by each loud speaker, and also provided data for the design of the equalizing networks required to give an over-all flat response-frequency characteristic. If the system, including the air path from the loud speakers to one position in the auditorium, is made flat, it will not, in general, be flat for other positions or for other paths in the room. This variation in characteristic is due partly to the variation in the ratio of direct to reverberant sound, and partly to the fact that the sounds of higher frequency are absorbed more rapidly by the air during transmission.[6,7] This latter effect is of considerable importance; it depends upon the humidity and temperature of the air, and may cause a loss of more than 10 db in the high frequencies at the more distant positions in a large auditorium. Some compromise in the amount of equalization employed therefore is necessary. Probably the most straightforward procedure would be to design the networks according to the response curves obtained with the microphones near the loud speakers. This would insure that for both the response measurements and the pick-up the microphone characteristics would be the same, and any deviation from a uniform response in the microphones would be corrected for in this way, along with variations in the loud speaker output. This procedure was modified somewhat for the case under discussion, however, because by far the greater portion of the audience was at a distance from the stage such that they received a relatively large ratio of reverberant sound, and it was believed that a better effect would be achieved by equalizing the system characteristic in accordance with response measurements taken at some distance from the loud speakers.

CONTROL EQUIPMENT

In addition to the equalizing circuits used to obtain a uniform response characteristic, 2 sets of quality control networks which could be switched in or out of the 3 channels simultaneously were employed. One set modified the low frequencies as shown at *A*, *B*, and *C* of Fig. 5, while the other gave high frequency characteristics as shown at *D*, *E*, *F*, and *G*. These latter networks permitted the director to take advantage of the fact that the electrical transmission and reproduction of music permits the introduction of control of volume and quality which can be superimposed on the orchestral variations. Quality of sound can be divorced from loudness to a greater degree than is possible in the actual playing of instruments, and the quality can be varied while the loudness range is increased or decreased. Electrical transmission therefore not only enlarges the audience of the orchestra, but also enlarges the *capacity* of the orchestra for creating musical effects.

The quality control networks and their associated switches were mounted in a cabinet (Fig. 6) at the right side of the director's position. Continuously variable volume controls for the 3 channels were mounted on a common shaft and housed in the center cabinet of Fig. 6. A separate control for the center channel was provided when that was used for the soloist. In addition to the high quality channels certain auxiliary circuits were supplied to aid the smoothness of performance. Supplementing the order wire connecting all technical operators, a monitor circuit was provided in the reverse direction. The microphone was located on the cabinet before the director, and loud speakers were connected in the control rooms and on the stage with the orchestra, enabling the control operator to hear what went on in the auditorium and allowing the director to speak to the orchestra. Two useful signal circuits were employed; one giving the orchestra a "play" or "listen" signal, and at the same time connecting either the auditorium or the orchestra's loud speakers, respectively; the other being a "tempo" signal to the assistant director leading the orchestra that could be operated during the rendition of the music. The switches for the auxiliary circuits and the order wire subset are shown at the control operator's position at the left in Fig. 6.

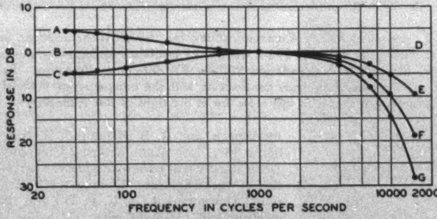

Fig. 5. Transmission characteristics of quality control networks used in the Philadelphia-Washington experiment

That a reproducing system may have quite different characteristics in different auditoriums is well illustrated in the case of the 2 halls considered here. From Fig. 3 it may be seen that in Constitution Hall the stage is built into the auditorium itself, and that there is no back stage space. The Academy of Music, however, has a large volume back stage. When the orchestra plays in the Academy the reflecting shell shown in Fig. 2 is used to concentrate the radiated sound energy toward the audience. When the reproducing system was set up in the Academy the shell could not be used because of the stage and lighting effects desired, and a large part of the energy radiated by the loud speakers at the low frequencies was lost back stage. The loss of low frequency energy is attributable partly to the fact that the loud speakers cannot well be made as directional for the very low frequencies as for the higher. The loss amounts to about 10 db at 35 cps, and becomes inappreciable at 300 cps or more, as measured in comparable locations in the 2 auditoriums. This difference in characteristics emphasizes the fact that for perfect reproduction the acoustics of the auditorium must be considered as a part of the system, and that in general the equalizing networks must have different characteristics for different auditoriums.

Fig. 6. Cabinets housing quality control networks and providing communication facilities for operation

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3. Optimum Reverberation Time for Auditoriums, W. C. MacNair. *Jl.* Acous. Soc. Am., v. 1, No. 2, part 1, Jan. 1930, p. 242.

4. Acoustic Control of Recording for Talking Motion Pictures, J. P. Maxfield. *Jl.* S.M.P.E., v. 14, No. 1, Jan. 1930, p. 85.

5. A High Speed Level Recorder for Acoustic Measurements, E. C. Wente, E. H. Bedell, K. D. Swartzel, Jr. Unpublished paper presented before the Acous. Soc. Am., May 1, 1933.

6. The Effect of Humidity Upon the Absorption of Sound in a Room, and a Determination of the Coefficients of Absorption of Sound in Air, V. O. Knudson. *Jl.* Acous. Soc. Am., v. 3, No. 1, July 1931, p. 126.

7. Absorption of Sound in Air, in Oxygen, and in Nitrogen—Effects of Humidity and Temperature, V. O. Knudson. *Jl.* Acous. Soc. Am., v. 5, No. 2, Oct. 1933, p. 112.

News

Of Institute and Related Activities

Winter Convention Program Provides Attractive Technical and Social Activities

A SCHEDULE of events which has been coördinated to provide a good balance between both business and social activities has been arranged for the winter convention of the A.I.E.E. to be held during the 4 days of January 23–26, 1934, in the Engineering Societies Building, 33 West 39th Street, New York, N. Y. Eleven technical sessions to be held during the mornings and afternoons of the first 3 days will present some of the most recent developments in electrical engineering. In the evenings a smoker, the Edison Medal presentation, a demonstration of transmission and reproduction of music, and the dinner-dance will be held. Special entertainment also is being arranged by the ladies entertainment committee, and will include a luncheon-bridge. Friday, the last day of the convention, will be devoted entirely to inspection trips; in addition, arrangements have been made to visit points of interest at other times. Altogether, the convention, which begins on Tuesday and ends on Friday, will be crowded with activity. In addition to this program, there will be a meeting of the board of directors at Institute headquarters on Monday, January 22, at 2:15 p.m., the day preceding the opening of the convention.

The New Brunswick, N. J., station of R.C.A. Communications, Inc., which is included on an inspection trip to be held Friday, January 26, 1934, during the Institute's forthcoming annual winter convention. Shown here are 2 Alexanderson 200-kw 27,000-cycle alternators. Behind the units, at the left, are the radio frequency transformers, with the compensating rheostats at the rear. Water pumps, not shown in this view are at the right of the alternators

SCHEDULE OF EVENTS

A summarized schedule of events follows. Capital letters A, B, etc., denote technical sessions.

Tuesday, January 23

9:00 a.m.	Registration
10:00 a.m.	Opening of convention
10:30 a.m.	A—Protective devices B—Transportation
2:00 p.m.	C—Symposium on electric power switching
6:00 p.m.	Smoker

Wednesday, January 24

10:00 a.m.	D—Power transmission E—Education Meeting of committee on education and committee on Student Branches
1:00 p.m.	Ladies luncheon and bridge
2:00 p.m.	F—Communication; symposium on transmission and reproduction of speech and music in auditory perspective G—Symposium on electric furnaces
8:15 p.m.	Edison Medal presentation Transmission and reproduction of speech and music in auditory perspective

Thursday, January 25

10:00 a.m.	H—Power distribution I—Electrical machinery
2:00 p.m.	J—Electrical machinery K—Electrical measurements
7:00 p.m.	Dinner-dance
9:00 p.m.	Dance and buffet supper

Friday, January 26

All day	Inspection trips

TECHNICAL SESSIONS

The tentative technical program as announced in ELECTRICAL ENGINEERING for December 1933, p. 928–30 is complete except for the following additional session and papers:

On Wednesday, January 24, at 10:00 a.m., a session on education will be held combined with a joint meeting of the committee on education and the committee on student branches. At this session it is expected to have Dean Doherty say a few words regarding the special series of articles on post college education now scheduled for month-by-month publication in ELECTRICAL ENGINEERING. A brief abstract of the present activities of the committee on education and the committee on Student Branches will be presented by L. A. Doggett, chairman of both committees. Then a paper will be presented on "The University of Pittsburgh-Westinghouse Graduate Program" by H. E. Dyche, University of Pittsburgh, and R. E. Hellmund, Westinghouse Elec. and Manufacturing Company. Dean Barker will review to date the activities of the Engineers' Council for Professional Development (E. C. P. D.) and the meeting will conclude with discussion of the Dyche-Hellmund paper, other items referred to above, and any new business.

The symposium on electrical power switching to be held on Tuesday, 2:00 p.m., will be opened with an introduction prepared by A. H. Lovell, University of Michigan.

At the communication session to be held on Wednesday, 2:00 p. m., the symposium on long distance transmission and reproduction in auditory perspective of symphonic music will be preceded by the presentation of a paper entitled "Stabilized Feedback Amplifiers" by H. S. Black, Bell Telephone Laboratories, Inc. The following paper has been added to the abovementioned symposium: "Loud Speakers and Microphones" by E. C. Wente and A. L. Thuras, Bell Telephone Laboratories, Inc.

The symposium on electric furnaces will also include an additional paper entitled "Iron and Its Production in the Cupola and the Electric Furnace" by M. V. Healey, General Electric Co.

As all of the papers for the winter convention program will have been published in advance of the convention, it is expected that exceptionally valuable discussions will take place at the meetings. Winter convention papers published in this issue and the 2 issues immediately preceding it have been designated by a star before the title in the table of contents. The only paper not published in these issues is the one entitled "Power Limit of a Transmission System" by W. S. Peterson which appeared in Electrical Engineering for August 1933, p. 569–72.

Edison Medal Presentation

The Edison Medal will be presented to Dr. Arthur E. Kennelly in the engineering auditorium on the evening of Wednesday, January 24, at 8:15 p.m. The medal has been awarded to Dr. Kennelly "for meritorious achievements in electrical science, electrical engineering, and the electrical arts as exemplified by his contributions to the theory of electrical transmission and to the development of international electrical standards." Further details of this award are included in a "personal" item on p. 232 of this issue. In view of the limited seating capacity, admission this year will be by ticket only.

Transmission and Reproduction of Speech and Music in Auditory Perspective

The following statements prepared by Bell Telephone Laboratories, Inc., give the highlights of the convention's most striking demonstration:

"The technical features of this accomplishment in telephonic communication are to be presented in a symposium of papers by Bell System engineers at the midwinter convention of the American Institute of Electrical Engineers on the afternoon of January 24, 1934. On the evening of that day, as part of the convention program, there will be a demonstration of this new communication system in the auditorium of the Engineering Societies Building, 29 West 39th Street, New York. This demonstration, in charge of Dr. Harvey Fletcher, physical research director, Bell Telephone Laboratories, will illustrate the character and range of the effects that can be produced with this system.

"During the course of this demonstration Dr. Fletcher will describe the essential apparatus of the system and demonstrate its applicability to reproducing, with complete illusion of reality, a variety of sounds including speech and orchestral music.

"This system of electrical communication was briefly reported upon to the National Academy of Sciences in April 1933, in a paper by Dr. F. B. Jewett, vice-president of the American Telephone and Telegraph Company and president of Bell Telephone Laboratories. At that time a public demonstration of the new equipment was given in which a program of the Philadelphia Orchestra was transmitted from Philadelphia and reproduced with exact auditory perspective upon the stage of Constitution Hall in Washington. The physical characteristics of the system also, were at that time briefly described by Dr. Fletcher and demonstrated through a few experiments.

"The forthcoming symposium of papers will be the definitive presentation of the technical features of this accomplishment; and Dr. Fletcher's program of demonstration, an equally complete illustration of the remarkable range and unique psychological effects of the system.

"During the week following the A.I.E.E. convention similar demonstrations will be given through the courtesy of Dr. Fletcher and the Bell Laboratories to the following societies: Institute of Radio Engineers, Society of Motion Picture Engineers, Acoustical Society of America, and the New York Electrical Society."

Because the seating capacity of the auditorium is limited and a large demand is anticipated for seats, admission will be by ticket only. These may be obtained without charge, at the convention registration desk. The demonstration will be held immediately after the Edison Medal presentation.

Entertainment and Social Activities

The smoker will be held in the Engineering Societies Building on Tuesday evening, January 23, at 6:00 p.m. In addition to a buffet dinner there will be movies and an excellent show in the auditorium. Tickets will be $2.75 per person and cover all events.

Annual Dinner-Dance Presents Novel Features This Year

The annual A.I.E.E. dinner-dance will be held Thursday, January 25, at the Waldorf Astoria Hotel, Park Avenue at 50th Street. As an innovation, it is to be a combination dinner-dance and dance-buffet supper. All the pleasurable features of previous years associated with the A.I.E.E. dinner-dances will be retained, but for those members and their guests who prefer to omit the formal dinner, the dance-buffet is offered. Music is by George Ellner's Orchestra. Following are the costs of tickets:

Dinner and dance reservation at $5.
Dance and buffet supper at $3.
For dinner-dancers an additional $1 to include the buffet-supper

The program is as follows:

7:00 p.m. Reception to President Whitehead—Basildon Room
7:30 p.m. Annual dinner—Astor Gallery
9:00 p.m.–2 a.m. Dancing—Jade Room
Buffet-supper service from midnight to 2:00 a.m.—Astor Gallery

The Basildon and Jade Rooms, together with the Astor Gallery, all fine examples of architectural art, are so equipped as to afford an excellent setting for this occasion. A most tempting dinner menu has been prepared and Oscar has assured us that he will make the most of this first opportunity

Fairchild Aerial Surveys Inc., Photo

An airplane view of lower Manhattan, looking across the East River, and with the Hudson Avenue generating station of the Brooklyn Edison Company in the foreground. New York City, which presents not only many striking scenes, but also many points of considerable engineering interest, is as usual the setting for the annual winter convention of the Institute, to be held this year, January 23–26. Back of the Hudson Avenue station and slightly to the left may be seen the older Gold Street station of the Brooklyn Edison Company, and beyond that, first, Manhattan Bridge, and then Brooklyn Bridge, with the Burling Slip station of the New York Steam Corporation just visible across the tops of the bridges, and almost shadowed by the tall buildings behind it

to "sell" us on the Waldorf. Transportation by subway is convenient and parking facilities will be provided by the Waldorf for a moderate fee.

Tables will be laid for 8 or 10 places. Send requests for tickets to the A.I.E.E. dinner-dance committee, 33 West 39th Street, New York City, and make checks payable to H. H. Henline, national secretary. Every effort will be made to comply with requests for the seating arrangements of members and their guests. To assist the committee in making arrangements, please purchase tickets early.

INSPECTION TRIPS

The inspection trips committee will endeavor to make available to the membership opportunities to visit a number of points of interest, some of which have been chosen because of their relationship to subjects covered in the technical program. It is planned to arrange for privileges to visit the following points on one or more days:

1. Electrical switch galleries, Hudson Avenue generating station, Brooklyn Edison Company
2. Roseland switching station, Public Service Electric and Gas Company, N. J.
3. 132-kv transformer substation, Pennsylvania Railroad
4. A-C calculating board, Pennsylvania Station, New York
5. Electric locomotive, Pennsylvania Railroad
6. Carrier current protective relays, Dunwoodie substation, 132-kv connection between generating stations in New York City with Niagara Hudson System
7. Electrical Testing Laboratories
8. Operating rooms of commercial telegraph companies
9. Electrical Research Products, Inc.
10. Electrical Institute of the Electrical Association of New York, Inc.
11. New York Museum of Science and Industry

Tentative plans are in progress for the arrangement of a special all-day motor bus trip to be made on Friday, January 26, over a route covering a large area in the northern part of the State of New Jersey, stopping for inspection of commercial long-wave and short-wave radio communication stations. The route will be chosen so as to include several points of historic and scenic interest as well. Some of the features of the trip are: Holland vehicular tunnel; elevated express highway; New Brunswick long-wave radio telegraph station of RCA Communications, Inc., where Alexanderson induction alternators may be seen; campus of Rutgers University; campus of Princeton University; Lawrenceville short-wave radio telephone transmitting station of the A. T. &. T. Co.; Washington Crossing State Park; Netcong short-wave radio receiving station of the A. T. & T. Co.; Morristown; and Newark. The cost of this trip and further information will be available at the inspection trips desk during the convention. Please make your reservations promptly upon arrival at the convention so that the committee may complete arrangements.

REGISTER IN ADVANCE

Fill in and post promptly the mail registration card which was included with the mailed announcement of the winter convention sent to members in nearby Districts. This will permit the committee to have badges ready and prevent congestion at the registration desk upon arrival. There will be a registration fee of $2 for nonmembers with the exception of Enrolled Students of the Institute, and the wives and children of members.

Bring Your E.E.'s to the Convention

In accordance with the provisions of the Institute's new publication policy, all papers scheduled for discussion at the winter convention have been published in ELECTRICAL ENGINEERING and thus circulated to the entire membership. Inasmuch as pamphlet copies of these papers will not be available, members attending the convention may wish to bring with them their August, November, and December 1933, and January 1934 issues.

Reservations for hotel accommodations should be made by writing directly to the hotel preferred.

REDUCED RAILROAD RATES

Fare and one-third for the round trip over the same route will be available to members and guests, provided 100 certificates are validated at the registration desk. Consult your local ticket agent regarding the territory and dates applicable as all passenger associations have not granted reduced rates. Obtain your certificate authorized by the railroad passenger associations.

A.I.E.E. Executive Committee Meets

In accordance with action of the board of directors, in October 1933, a meeting of the executive committee of the American Institute of Electrical Engineers was held at Institute headquarters, New York, N. Y., December 8, 1933, in place of the regular December meeting of the board of directors.

Present were: John B. Whitehead, chairman; H. P. Charlesworth, J. Allen Johnson, Everett S. Lee, E. B. Meyer, C. E. Skinner, and W. I. Slichter, of the executive committee; A. E. Knowlton and R. W. Sorensen, members of the board of directors; and H. H. Henline, national secretary.

In memory of Past-President Calvert Townley, the committee adopted a resolution, which is published elsewhere in this issue.

A report of a meeting of the board of examiners held on November 15, 1933, was presented and approved. Upon the recommendation of the board of examiners, the following actions were taken upon pending applications: 1 applicant was elected and 4 were transferred to the grade of Fellow; 11 applicants were elected and 15 were transferred to the grade of Member; 45 applicants were elected to the grade of Associate; 767 Students were enrolled.

The finance committee reported disbursements amounting to $18,740.83 for the month of November. Report approved.

Upon the recommendation of the Sections committee, approval was given to a petition for authority to organize a New Orleans Section of the Institute, with a territory embracing the entire state of Louisiana.

Professor W. I. Slichter was reappointed a representative of the Institute on the library board of the United Engineering Trustees, Inc., for the 4-year term beginning January 1, 1934.

The following were appointed as representatives of the Institute upon the assembly of American Engineering Council for the year 1934: C. O. Bickelhaupt, F. J. Chesterman, William McClellan, C. E. Stephens, John B. Whitehead, and H. H. Henline, alternate.

It was decided that the January meeting of the board of directors will be held on Monday afternoon, January 22, 1934.

Other matters were discussed, reference to which may be found in this and future issues of ELECTRICAL ENGINEERING.

Nominating Committee Announces Candidates

A complete official ticket of candidates for the Institute offices that will become vacant August 1, 1934, was selected by the national nominating committee at its meeting held at Institute headquarters, New York, N. Y., December 7, 1933. This committee, in accordance with the constitution and by-laws, consists of 15 members, one selected by the executive committee of each of the 10 Geographical Districts and the remaining 5 selected by the board of directors from its own membership.

The following members of the committee were present: C. R. Beardsley, Brooklyn, N. Y.; H. P. Charlesworth, New York, N. Y.; A. F. Darland, Tacoma, Wash.; O. J. Ferguson, Lincoln, Neb.; P. S. Harkins, Philadelphia, Pa.; A. H. Hull, Toronto, Ont.; G. A. Kositzky, Cleveland, Ohio; F. H. Lane, Chicago, Ill.; Everett S. Lee, Schenectady, N. Y.; W. E. Mitchell, Atlanta, Ga.; L. W. W. Morrow, New York, N. Y.; G. H. Quermann, St. Louis, Mo.; R. W. Sorensen, Pasadena, Calif.; A. C. Stevens, Schenectady, N. Y.; H. R. Woodrow, Brooklyn, N. Y.

Following is a list of the official candidates selected by the committee:

FOR PRESIDENT

J. Allen Johnson, chief electrical engineer, Buffalo, Niagara & Eastern Power Corporation, Buffalo, N. Y.

FOR VICE-PRESIDENTS

North Eastern District (No. 1): W. H. Timbie, professor of electrical engineering and industrial practice, Massachusetts Institute of Technology, Cambridge, Mass.

New York City District (No. 3): R. H. Tapscott, vice-president, New York Edison Company, New York, N. Y.

Great Lakes District (No. 5): G. G. Post, vice-president, Milwaukee Electric Railway & Light Company, Milwaukee, Wis.

South West District (No. 7): F. J. Meyer, vice-president in charge of operation, Oklahoma Gas &

Electric Company, Oklahoma City, Okla.

North West District (No. 9): F. O. McMillan, research professor of electrical engineering, Oregon State College, Corvallis, Ore.

FOR DIRECTORS

F. M. Farmer, vice-president and chief engineer, Electrical Testing Laboratories, New York, N. Y.

N. E. Funk, vice-president in charge of engineering, Philadelphia Electric Company, Philadelphia, Pa.

H. B. Gear, assistant to the vice-president, Commonwealth Edison Company, Chicago, Ill.

FOR NATIONAL TREASURER

W. I. Slichter, professor of electrical engineering, Columbia University, New York, N. Y.

The constitution and by-laws of the Institute provide that the nominations made by the national nominating committee shall be published in the January issue of ELECTRICAL ENGINEERING. Provision is made for independent nominations as indicated in the following excerpts from the constitution and by-laws:

CONSTITUTION

SEC. 31. Independent nominations may be made by a petition of twenty-five (25) or more members sent to the national secretary when and as provided in the by-laws; such petitions for the nomination of vice-presidents shall be signed only by members within the District concerned.

BY-LAWS

SEC. 23. Petitions proposing the names of candidates as independent nominations for the various offices to be filled at the ensuing election, in accordance with Article VI, Section 31 (Constitution), must be received by the secretary of the national nominating committee not later than February 15 of each year, to be placed before that committee for the inclusion in the ballot of such candidates as are eligible.

On the ballot prepared by the national nominating committee in accordance with Article VI of the Constitution and sent by the national secretary to all qualified voters during the first week in March of each year, the names of the candidates shall be grouped alphabetically under the name of the office for which each is a candidate.

(*Signed*) National Nominating Committee
by H. H. HENLINE,
Secretary

BIOGRAPHIES OF NOMINEES

That those not personally acquainted with the nominees may know something of them and their qualifications for the Institute offices for which they have been recommended, brief biographical sketches are given on p. 230–2 of this issue.

Engineers Urged to Greater Activity in Local Affairs

Under the thought-provoking title of "Help Yourselves!" the following editorial prepared by the Professional Engineers' Committee on Unemployment, serving the metropolitan area of New York, N. Y., was released by the P.E.C.U. to the engineering societies:

"In a radio address, delivered on Sunday, October 15, 1933, our great leader of American thought in time of stress, the President, declared strongly against the policy of passing the relief-work 'buck' to the Federal Government. He declared that the community, the village, town, city, state—the ultimate unit in our social and economic scheme—must do its share and call upon Washington only as a last resort.

"To this pronouncement, the Professional Engineers' Committee on Unemployment, organized in 1931 to cope with problems of unemployment in the engineering profession, can cordially subscribe.

"It is not by a 3-billion-dollar public works program that enough people, especially professional engineers and trained technical men can be provided with employment.

"What kind of men will a program of road building, bridges, tunnels, public buildings, naval construction, employ? The vast majority will comprise laborers, sand-hogs, steel erectors, concrete-men and some building trade mechanics. The equipment required has been rusting in the yards for 4 years. It will probably be brought out, dusted off, oiled, and put to work. There will be little enough demand for new equipment, so that the effect upon factory production will not be conspicuously marked.

"But if each community will look around and see what work it can undertake, that will be another matter. There is hardly a village in the country which has not some neglected project or crying need for improvement ready to be undertaken at once. Water works, sewage disposal, street widening, transportation systems, airports, municipal buildings, paving, new equipment for police, fire, sanitary, hospital departments, bridges, docks, freight terminals, parks; slum clearance in which private capital is willing enough to interest itself with reasonable encouragment—all

In Memoriam

CALVERT TOWNLEY

ON November 27, 1933 there was removed from our ranks, Calvert Townley, thirty-second president of the American Institute of Electrical Engineers.

From the earliest days of his professional career, when on graduating from Sheffield Scientific School he entered the employ of the Brush Electric Light Company, down through his connections with the Boston subways, the N. Y., N. H., & H. electrification and his many years of affiliation with the Westinghouse Electric and Manufacturing Company, Calvert Townley exhibited an unusual ability to grasp quickly the technical details of the problems which confronted him, particularly as those details affected the managerial phases for which he was so often responsible. So also in his years of service devoted to the Institute and to the welfare of the profession which he had chosen, he exhibited the same quick grasp of detail and thorough understanding of problems as a whole. Entering the Institute in 1901 he became a Fellow in 1912. His executive ability soon brought him election as manager in 1905, vice-president in 1908 and president in 1919. He gave much of his time to the questions coming before the public policy committee serving as chairman for over 5 years. Recognition of his thorough understanding of the needs of the profession was indicated in his selection as chairman of the Committee on Development of the Institute and, likewise, his election to trusteeship in the United Engineering Society and the Engineering Foundation board.

Throughout his professional life, both before and since his presidency, he was constant in his active interest in the affairs of the Institute, especially in those questions pertaining to the dignity and elevation of the profession of engineering. At the time of his death he was giving freely of his counsel and time in important Institute activities of this type in the Coordination Committee of Engineering Societies. It would be difficult to overstate the value of his services to both Institute and profession. His loss is all the more serious at this time of agitation and uncertainty.

It is therefore with a keen sense of inability to evaluate in words the part which Calvert Townley has played in our ranks and the loss which the profession sustained when he passed on that we order this minute be spread upon the records, and that it be transmitted to his family and associates as an expression of appreciation and admiration from those who were privileged to work with him in the American Institute of Electrical Engineers.

—A.I.E.E. Executive Committee, Dec. 8, 1933 these are desperately needed in every community in the country, having now been neglected for years.

"And they would all employ engineers, not only in the work itself but in making the material and equipment necessary to carry it out. If all this were to be undertaken it would involve many more than 3 billions of expenditure. The normal building construction program amounts to 6 billions as does the steel industry and the automobile industry. In fact, our total years business added up to 88 billions of dollars in 1928.

"But, how to get this vast program under way? The answer is to bring pressure to bear in the individual community. And the engineer can do his share there, too, as a citizen as well as a technically trained, and, therefore, super-useful member of the community.

"The engineer is all too prone to sit back and watch the self-appointed governors of his home town, the local druggist, doctor, lawyer, banker, run the place, while he patiently awaits the result of their decisions. They elect themselves to the local board of supervisions, the State legislature, Congress, and settle, in their own political way, the engineering improvements which are to be made.

"Engineers! Wake up! Take a hand in your local government, the activities in your community. You know far more about the engineering needs of a town and how to execute it than the local politicians. Take the lead and get some of the local projects going. Organize the opinion of the substantial citizens. Get your newspaper interested. Take the side of good government. Towns can raise capital when individuals cannot.

"It is only by such capital investments that you and all engineers can live."

E.C.P.D. Committee on Professional Recognition Commented Upon by C. N. Lauer and Dean Barker

THE committee on professional recognition, one of the 4 working committees of the newly organized Engineers' Council for Professional Development, has already actively undertaken its duties and has accomplished tangible results. These are summarized in the following article prepared by Conrad N. Lauer, chairman of the committee, and J. W. Barker, the representative of the A.I.E.E. upon this committee. This article was prepared for ELECTRICAL ENGINEERING by Mr. Lauer and Dean Barker, at the request of L. A. Doggett (A'13, M'16), chairman of the Institute's committees on Student Branches and on education. The article by Mr. Lauer and Dean Barker follows:

E.C.P.D. Brings Engineering Groups Together

For the first time in the history of the engineering profession in the United States there has been organized a joint activity dedicated to the principle of assisting the individual engineer in his personal professional development. This organization is known as the Engineers' Council for Professional Development and brings together the 5 principal engineering societies—the American Society of Civil Engineers, the American Institute of Mining and Metallurgical Engineers, The American Society of Mechanical Engineers, the American Institute of Electrical Engineers, the American Institute of Chemical Engineers—together with the national society of engineering educators, the Society for the Promotion of Engineering Education, and the National Council of State Boards of Engineering Examiners. This is not a super-engineering society nor does it parallel or interfere with any of the existing established agencies. It is purely a coöperative project and operates only to recommend to its constituent bodies joint action leading toward the ideal of enhancing the professional development of the engineer. It operates only through recommendations to the member bodies, first as to policies and when such policies have been approved by the member bodies acting individually then the Engineers' Council again comes into play in recommending procedures to carry out these approved policies. It is highly important that every member of our American Institute of Electrical Engineers shall thoroughly understand these principles of action, particularly in considering the reports of the Engineers' Council for Professional Development and its various committees. The policies outlined in committee reports when approved by the Engineers' Council for Professional Development still do not become effective until the individual member bodies have severally taken favorable action upon the recommendations.

Scope of the E.C.P.D.

The Engineers' Council for Professional Development considers that its problem covers the period in the engineer's life running from the first evidence of his inclination to become an engineer to the time when he finally attains full recognition by the professional societies, the engineering educational institutions and the state as a full-fledged engineer competent to take responsible charge of engineering work in his particular field. To cover this range the Engineers' Council has set up 4 main committees on student selection and guidance, on engineering schools, on professional training, and on professional recognition.

Committee on Professional Recognition

This article is concerned primarily with the committee on professional recognition which is composed of the following members:

Conrad N. Lauer, chairman (Representing The A.S.M.E.). President, Philadelphia Gas Works; past-president, A.S.M.E.; former chairman A.S.M.E. committee on economic status of mechanical engineers.

Joseph W. Barker (M'26, F'30) (Representing the A.I.E.E.). Dean, school of engineering, Columbia University; chairman of committee on university relations, engineering division, National Research Council; chairman of committee on degrees of engineering schools of New York State.

Frederick M. Becket (Representing the A.I.M.E.). President, A.I.M.E.; president, Union Carbide and Carbon Research Corporation; vice-president, Electro Metallurgical Corporation.

Frederick L. Bishop (Representing the S.P.E.E.). Secretary, S.P.E.E.; professor of physics, University of Pittsburgh.

H. C. Parmelee (Representing the A.I.Ch.E.). Vice-president, McGraw-Hill Publishing Company; former chairman, A.I.Ch.E. committee on engineering education.

J. P. H. Perry (Representing the A.S.C.E.). Member of board of direction of American Society of Civil Engineers; vice-president, Turner Construction Company.

David B. Steinman (Representing the N.C.S.B.E.E.) President, New York State Society of Professional Engineers; former president National Council of State Boards of Engineering Examiners; consulting engineer of the firm of Robinson and Steinman.

This committee on professional recognition is concerned with recommending through the Engineers' Council for Professional Development to the member bodies for approval standards for entrance to the profession and the methods of establishing and maintaining them. If the profession is to improve the minimum professional and intellectual background of those servants of the public to be called engineers it must itself establish high standards for those qualifications which will render the engineer a valuable member of society. This involves emphasis on social, economic, and general cultural training as well as the maintenance of high technical standards of education and practice.

While such a procedure will also improve the status of the engineering profession in the eyes of those who use engineering services and in the view of other professions and the public, the primary purpose of all the activities of this committee is and should be directed toward improving the services which the qualified engineer can and must render to the public service.

Policy Adopted

To guide the committee in fulfilling its purpose the following policy has been adopted by the Engineers' Council for Professional Development:

"The profession should establish as the goal of attainment a series of qualifications for which the young man, whether graduate or non-graduate, may successfully strive continuously from the time he enters upon an engineering career. This goal of attainment, embodied in a certificate,[1] equivalent to the professional degree and having a value recognizable as adequate to entitle the holder to licensing or registration in a state, should be based upon the following features:

a. Certification should be earned, and not granted as a mark of honor.

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[1] When the recommendations stated later in this article have been approved by each of the member bodies the committee on professional recognition will be concerned with setting up a joint coöperative examining board, which may be the committee itself, or a subcommittee thereof, or an agency independent of the committee, to examine and certify to the profession those candidates who meet the minimum definition of an "Engineer," as later outlined in this article.

b. **The code of educational qualifications should be more advanced than graduation from college, yet attainable by both college and noncollege men.**

c. **The attainments should be tested individually by examination (written and oral) or the equivalent and not gauged by personal estimates and testimonials alone.**

d. **Educational qualifications should comprise scientific, technical, economic, and civic knowledge of a mature order.**

e. **The code of experience qualifications should normally make the age of certification fall between 25 and 30.**

f. **The ultimate certification into the profession should be the objective to which both the colleges and the professional societies should exert their influence. To this end the colleges should be encouraged to aid by granting the professional degree only to those who have been thus certified.**

g. **The certificate into the profession should be the means by which the state registration boards would with confidence recognize those essentials which they observe as requisite for the registration of engineers.**

h. **And, similarly, the certificate into the profession should be *prima facie* evidence of technical proficiency for admission into the corporate membership of the societies.**

"By such a progressive educational program involving selection of proper material, its supervised education, intimate contact with the profession during the apprenticeship state and the attainment of definite specified educational requirements with concurrent recognition by professional societies, educational institutions, and state laws, it is believed that an identity would be attained by which those who have not developed experience and maturity of engineering judgment would be recognized as assistants in the engineering field and those who have attained engineering maturity would have an identity universally recognized by the profession itself and the public at large. It is believed that this definition of the engineering profession will be of immeasurable benefit."

Policy as Affecting Colleges, State Boards, and Societies

It should be noted in this policy the Committee has suggested placing the question of professional recognition on a more scientific basis. It recommends dispensing with testimonial opinion alone and substituting therefor fact as determined by actual examination. This policy furthermore attempts to avoid duplication either of examination by the engineer or by the bodies concerned with his professional training. As an example, under (*f*) above it does not require that the engineering Alma Mater shall be required to grant the professional degree to engineers who have been thus certified but suggests that those engineering colleges desiring to grant professional degrees to their graduates shall coöperate in the general program by not granting the professional degree prior to the attainment of this certification. Many of our engineering schools at the present time grant professional degrees to such of their graduates as have been in the practice of engineering for a certain number of years and who submit to the engineering faculty concerned a suitable thesis on some phase of their professional activity. It is quite probable that when the policies of the committee on professional recognition have been approved by the member bodies and this committee turns its attention to the modus operandi of certification it will require as a part of the final examination for professional recognition a thesis or similar work covering the most important phase of the candidate's professional activity. Such a thesis could be submitted simultaneously to the engineering faculty concerned as well as to the certifying board and if the candidate is granted certification the engineering school could, if it so desired, then grant the professional degree.

Similarly under (*g*) above the various state licensing and registration boards could also recognize this certificate and the examination leading up to the certificate as covering those essentials which they are required to observe as requisite for the state registration of engineers. This would again avoid duplication of work both by the candidate and by the responsible body. It should also be noted that there is nothing in this policy which requires the candidate to become licensed by any state unless the type of work in which he is then or later becomes engaged requires such registration.

As another example under (*h*) above there is nothing which requires a candidate to assume corporate membership in his professional society when he secures the certificate. It simply means that the certificate is recommended for adoption by each of the professional societies as a necessary and prima facie evidence of proficiency for admission to the corporate membership grade.

Minimum Qualifications for an "Engineer"

The committee on professional recognition reviewed in great detail the present requirements for recognition embodied in the grades of membership of the participating societies, in the "model" law for registration and licensing of engineers and in the practice of awarding professional degrees. Lack of uniformity seemed prevalent in all of these requirements and the need was apparent that a united profession must have a minimum definition of an engineer. Based upon this study the following was adopted by the committee, by the Engineers' Council for Professional Development, and to be recommended to the participating societies as the minimum qualification for an engineer:

a. **Graduation from an approved course in engineering of 4 years or more in an approved school or college; a specific record of an additional 4 years or more of active practice in engineering work of a character satisfactory to the examining body (the examining body, in its discretion may give credit for graduate study in counting years of active practice); and the successful passing of a written and oral examination covering technical, economic, and cultural subjects and designed to establish the applicant's ability to be placed in responsible charge of engineering work and to render him a valuable member of society:**

or alternatively

b. **Eight years or more of active practice in engineering work of a character satisfactory to the**

May Be Visited During the Winter Convention

ABOVE is shown the 132-kv Elmsford substation of the Westchester (N. Y.) Lighting Company, which incorporates an unusual design of 132-kv structure. In the picture at the side is shown carrier current equipment at the Dunwoodie station of the Yonkers (N. Y.) Electric Light and Power Company; this is part of the 132-kv Niagara-Hudson interconnection. Both of these stations may be visited by those attending the Institute's winter convention, January 23–26, 1934.

examining body and the passing of written and oral examinations designed to show knowledge and skill approximating that attained through graduation from an approved engineering course and also examinations written and oral covering technical, economic, and cultural subjects designed to establish the applicant's ability to be placed in responsible charge of engineering work and to render him a valuable member of society.

SOCIETY MEMBERSHIP GRADES

It should be noted that there is no attempt on the part of the committee to recommend for adoption one solitary road to recognition as an engineer but the committee recognizes that competent engineers may be trained either in the formal processes in our educational institutions or in the school of practice. It should also be noted that the committee recommends that formal education alone or practice alone cannot produce a competent engineer. The combination of study and practice is necessary. In this connection the committee feels that there are a minimum of 3 large groups of persons in the engineering field who may be roughly separated as follows. A student who is a person matriculated in an approved engineering school or one who is engaged in practice and is pursuing on his own initiative studies comparable with those given in an engineering school. It is anticipated that the committee on professional training of the Engineers' Council for Professional Development will so organize its work as to provide possibilities to the young apprentice who has not gone to an engineering school to carry out these fundamental engineering studies on his own initiative. These 2 groups constitute our student class and consequently the committee on professional recognition has recommended that the professional societies concerned should seriously consider amending their student membership rules and specifications to bring these groups into the societies as "student members." After graduation from an approved engineering school or after the noncollege student has passed equivalent written and oral examinations he becomes in essence an engineer in training or a junior engineer. Consequently the committee has recommended that the participating societies seriously consider amending their membership rules and specifications to provide for "junior members" for this class of persons. This "junior membership" would cover the minimum period until the person has met the minimum qualifications of an engineer as outlined above, whereupon he should become eligible for the "member" grade.

Uniformity in the grades of membership in the various societies and in conformity with the above suggested grades and designations are both logical and highly desirable. At the present time there is little uniformity between our various societies and great confusion exists in the minds of the public at large as to the meaning of our various society membership designations. A simple, rational, logical, and uniform nomenclature and specification has therefore been recommended and it is hoped that the societies may adopt this as a logical ideal toward which to work. It should be appreciated, of course, that nothing completely revolutionary to the present set-up should be attempted. With this in mind the Engineers' Council did not approve any recommendation for "fellow" grade, as being outside the purview of the council. Secondly, the Engineers' Council made the following statement: "These recommendations, however, are not intended to exclude the affiliations of other persons with any constituent society in a capacity other than the grades of membership indicated." Third, the Engineers' Council recommended that these specifications for "student member," "junior member," and "member" be regarded as "minimum."

FURTHER ACTION TO BE TAKEN

In accord with the policy first outlined in this article the grade of membership, the license, and the professional degree should be in substantial agreement with the minimum definition of an engineer. The committee urges that steps be taken to place this view before the faculties of engineering schools for consideration so that in time the grades of professional recognition when granted may be uniform. In this connection the committee on professional recognition and the Engineers' Council for Professional Development recommended through the Society for the Promotion of Engineering Education that the faculties of engineering schools give consideration to the bestowal of professional degrees only to those who have attained the minimum standard, the actual vote of the Engineers' Council being as follows: "That when the recommendations for minimum definition and standard grades of membership are approved by the participating bodies, then E.C.P.D. make the suggestion through S.P.E.E. that the professional degree be granted only to those who meet the minimum definitions."

Throughout this article the phrase "approved school" has been used with the knowledge that the committee on engineering schools has this matter under consideration and that a scheme for accrediting schools will be forthcoming which would result in a list of approved schools. The phrase therefore should be viewed in the light of a possible report from the committee on engineering schools which was made at the meeting of the Engineers' Council by the committee on engineering schools and was adopted for recommendation to the participating bodies. It is beside the point whether accrediting is desired or not. It is a fact which must be met that various of the state laws require the setting up of a list of approved schools and it is highly desirable that such a list be uniform throughout the country.

The committee on professional recognition is fully cognizant of the fact that acceptance by the participating bodies of these various recommendations including the minimum definition of an engineer will not of themselves raise the standard of the profession. The committee is therefore bending its efforts to a consideration of the mechanism, scope, and content of examinations and other procedures for measuring the achievement of standards for recognition by the individual in order that it may be ready when the participating bodies have approved the policy and recommendations to make additional recommendations for the modus operandi. The committee again stresses the fact that these recommendations are recommendations and are not compul-

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Great Britain's First Streamlined Rail Car

ACCORDING to The Travel and Industrial Development Association of Great Britain and Ireland, the first streamlined rail car to be used in Great Britain was placed in service in a "press" run December 1, 1933. It is used by the Great Western Railway on one of its suburban services. The journey of 36 miles between London and Reading was covered in this run in 39 min 52 sec and in 42 min 24 sec, for each of 2 nonstop runs; the maximum speed obtained was 62 mph. The car, of unique design, is the outcome of exhaustive tunnel tests to reduce wind resistance, which at normal speed requires more power to overcome than the driving of the car along the rails. The car, shown above, is 62 ft long, and 11 ft 4 in. high. It weighs 20 tons and has been designed for a maximum speed of 60 mph. Seating capacity is for 69 passengers, the leather covered seats being arranged in pairs, permanently placed back-to-back. The sides of the car extend to within one foot of the track, so that practically the whole of the car, including wheels, is enclosed in a streamlined case. Everything possible has been enclosed, even to the head and tail lamps, controlled from the driver's seat, which are fitted flush with the case. It is stated that the effect of this streamlining has been to reduce wind resistance to $^1/_8$ of that encountered by a similar square-ended car.

sory upon any organization until they have been adopted by the proper body of that organization. Coöperation between all our various engineering bodies looking to the ideal of enhancing the professional development of each and every engineer in this country is the keynote of all the work of the Engineers' Council for Professional Development and the work of the committee on professional recognition with which this article is concerned. To establish a guild or union is not the concept which motivates anybody concerned with this movement. Before we can convince the public that the engineer is truly a professional man we must coöperate in developing a professional status and in this coöperation it is desirable that every member of the profession shall be cognizant of and in sympathy with the ideals for which we are striving.

Primary Considerations Relating to Steam, Electric, and Diesel-Electric Traction. Identified as being based upon actual operating conditions on British railways, an article carrying the foregoing title and published in *World Power* for November 1933, p. 247–55, surveys the technical and financial positions of the 3 forms of railroad traction. The paper originally was presented before the "British" Institution of Civil Engineers. The article presents perhaps the most detailed study of its kind that has appeared, and the tables and illustrations contain a mass of essential information on railway conditions. The figures are, however, based upon estimates and applied to British conditions.

San Francisco Section Stimulates Student Participation

Student participation in the activities of the Institute's San Francisco, Calif., Section undoubtedly will be broadened and stimulated by policies announced by Section Chairman W. C. Smith at the September 29, 1933, meeting of the Section. The plan is that at each meeting a Student will present a 5-min biography of one of the pioneers in electrical development. At the September 29 meeting, the plan was inaugurated by a 5-min biographical sketch of Ampere, presented by a Student.

Further to stimulate the attendance of Enrolled Students at Section meetings, the Section has inaugurated the policy of absorbing for all students attending, half the price of the regular dinner that precedes Section meetings.

Chemistry Industry Medal Awarded to J. G. Vail. The Chemical Industry Medal of the American Section of the Society of Chemical Industry was presented to J. G. Vail, of the Philadelphia Quartz Company, at a meeting held in New York, N. Y., November 3, 1933. The meeting was held jointly with the American Chemical Society, the Electrochemical Society and the Société de Chimie Industrielle. This is the first award of what is called the "Chemical Industry Medal" which takes the place of the Grasselli Medal awarded annually for several years by this society. The new medal is awarded Mr. Vail in recognition of his work on sodium silicates in industry. He joined the chemical department of the Philadelphia Quartz Company in 1905, and is now a vice-president and chemical director.

High Voltage X Ray Tubes Are Compared

A comparison has been made at the U.S. Bureau of Standards of the X ray output as a function of the applied voltage for different types of high voltage tubes. The complete results of this work are contained in research paper No. 595, published in the September 1933 number of the "Bureau of Standards Journal of Research."

The comparison was made for 2 thin glass X ray tubes, 5 thick glass tubes, and 1 metal-centered tube on several generators of different voltage wave form. Thin glass tubes show about 15 per cent greater output than thick glass tubes on constant potential, while the metal-centered tube gave about 15 per cent less output. At any given effective (rms) voltage, the outputs of all glass tubes or all generators were nearly the same, and equal to the output on a constant potential of the same value. Likewise, at a given effective voltage, the quality (full absorption curve) was the same for all tubes on all generators.

Outputs of all tubes at a given peak voltage varied over a range of 25 per cent between tubes and between different generators. The metal-centered tube output varied widely between half and full wave rectification at equal peak voltages. The same tube, however, gave the same output at any given effective voltage supplied by any generator.

Development of Mines and Men Traced in "Porphyry Coppers"

Whether or not all electrical engineers will agree with John Hays Hammond, in his foreword to Parson's "Porphyry Coppers," that major developments in the electrical industry have come about through the assurances of large supplies of copper is not known. However, the mining engineer feels assured that his professional colleagues in the electrical industry at least will admit that the enormous tonnages of copper that became available in the decade commencing with 1910 have had a marked influence upon electrical developments as well as on the face of nature in the western mountains.

Mr. Parsons, now secretary of the American Institute of Mining & Metallurgical Engineers, is singularly well equipped for the task he has undertaken—the writing of a chronicle of engineering in the 2 Americas. Educated in Utah, Mr. Parsons has spent much of his professional career among the men who were actively engaged on these enterprises. His clear and attractive style, polished by service on the editorial staffs of the *Mining and Scientific Press* and the *Engineering and Mining Journal*, has humanized the history and technology of the big copper mines treated in the pages of "The Porphyry Coppers."

In his book the author points out through numerous examples that the entire success of these mining projects was due to engineering principles, correctly applied and amplified by the ingenuity and steadfast courage of a large number of American engineers. Backed by capital, mainly American and British, these engineers "have converted huge ore deposits in many countries into the big metal mines of the world." Throughout the pages names of men still active in mining and financial circles appear in settings markedly different from their earlier surroundings where they are so vividly depicted as eager searchers for ore. Although the book is primarily a story of and for the mining engineer, it has much of interest to anyone who ever has felt the call of far away places or the desire to get rich in a hurry by buying stocks in some mining enterprise with a flowery name.

Mining engineers realize that the author in selecting his title has chosen the term "The Porphyry Coppers" judiciously. Presumably only a geologist or a mining engineer will be particularly interested in the fact that not all the great mines that are discussed are in porphyritic deposits. The author himself points out that there are other copper deposits, some of which have been exploited profitably, that are not included. The author confines the term to those mines having enormous tonnages of low grade ore, in which the minerals occur disseminated over large areas. From these deposits, considered of doubtless economic value 30 years ago, copper has been won by large scale production methods.

It is interesting to note that the porphyry deposits, which have yielded more than 17 billion pounds of copper and have reserves of more than 100 billion pounds of copper in unmined ore, all had been worked prior to 1900. The Chino mine in New Mexico may have been the scene of the first mining activity in the Western hemisphere. At Chuquicamata, Chile, copper had been mined by the Incas in the 16th century. However, it was not until Jackling had pioneered the porphyry coppers with Utah Copper in Bingham Canyon, Utah, that the potential extent of the various porphyry coppers came to be realized.

The subject matter of the book includes the stories of 12 remarkable mines, 9 in North America and 3 in South America. Considerably more than half the book is devoted to historical summaries of the development of these great mines from their humble beginnings as prospects to their fruition as profitable enterprises. The technology of mining, including exploration, ore extraction, and treatment processes, so markedly advanced by engineers connected with those various companies, is treated most adequately in several chapters. Throughout the discussion the author emphasizes the effect these vast enterprises have had upon the social and economic development of the Western states—Utah, Nevada, Arizona, and New Mexico—and upon Chile, sister republic in South America. Their effect upon the "Building of the West" has been unquestioned for the past 2 decades and this marked influence will continue for many years to come.

The title of the first chapter—"An

Achievement of Engineers"—would serve admirably as a subtitle of the book as a whole. The author has stated that "Whatever Power is reponsible for the Universe made ore deposits; but mines are made by the genius of men." He might have added the corollary which his book so clearly indicates—mines make men.

"The Porphyry Coppers" by A. B. Parsons is the first of the Rocky Mountain Fund Monographs to be published (1933) by the American Institute of Mining and Metallurgical Engineers, 29 West 39th Street, New York, N. Y. The book is cloth bound, 6 x 9 in. in size; its 581 pages are well illustrated, and its price is $5.—H. M. Lawrence.

Electrically Controlled Wind Tunnel Completed at Case. A large wind tunnel for testing wind pressures and their effects on airplane structures, buildings, etc., has recently been completed at the Worcester Reed Warner Laboratories, Case School of Applied Science, Cleveland, Ohio. The tunnel, which is built of heavy sheet metal reinforced with angle-iron, is approximately 30 ft long. Its cross-sectional area is 81 x 81 in. at the largest part, and tapers down to 3 by 3 ft at the semi-open section where the test models or objects are placed. A sensitive counterbalance system of suspension wires permits accurate measurement of the force or "drag" exerted by the wind upon the object and a draft gage connected to a "pitot tube" enables the velocity of the airstream to be determined readily. To assure a wide range of steady non-pulsating airflow at all velocities from that of a gentle breeze to the equivalent of a destructive tornado, special adjustable voltage equipment was designed by the Electric Generator and Motor Company. A 75-hp 3-phase squirrel-cage induction motor direct coupled to a 50-kw d-c generator was installed. The generator is separately excited from a small machine which also supplies the separately excited fields of the fan-motor in the wind tunnel. The main generator armature is arranged to feed the armature of the fan motor. In this way, the required speed variation of the fan is obtained without any tendency toward instability of control at low speeds.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. Electrical Engineering will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Slide Rule Calculation of $\sqrt{a^2 + b^2}$

To the Editor:

The method here set forth makes use of the well-known expansion of $\sqrt{a^2 + b^2}$ in terms of the descending continued fraction; viz:

$$\sqrt{a^2 + b^2} = a + \frac{b^2}{2a+}\,\frac{b^2}{2a+}\,\frac{b^2}{2a+}\cdots$$

Divide b^2 by $2a$ and add the quotient to $2a$ to form a new divisor, and repeat until a constant quotient is attained. Add this quotient to a to secure the final answer.

Even when a and b are equal 4 movements of the cursor are all that are required. For rapid convergence b is taken to be the smaller of the 2 numbers but that is not essential.

The method gives more accurate results than the direct method of squaring and adding and extracting the root and is faster.

Example:

$$\sqrt{2^2 + 1^2} = 2 + \frac{1}{4+}\,\frac{1}{4+}\,\frac{1}{4+}\cdots$$

(1) $\frac{1}{4} = 0.25$

(2) $\frac{1}{4.25} = 0.235$

(3) $\frac{1}{4.235} = 0.236$

Hence $\sqrt{2^2 + 1^2} = 2.236$ by slide rule, with the last figure definite. From a table $\sqrt{5} = 2.2361$.

Very truly yours,
V. G. Smith (A'26)
(Asst. Prof. of Elec. Engg.
Univ. of Toronto, Ontario, Can.)

A New Method of Calculating Circuits

To the Editor:

The object of this paper is to attempt to show, and in a somewhat different way perhaps than that contemplated by W. B. Kouwenhoven and M. W. Pullen in their article "A New Method of Calculating Circuits" (see Electrical Engineering for November 1933, p. 776–9), the exact foundation upon which this method rests.

In a general theory, it is not necessary to emphasize one section of circuit over another. The load impedance may therefore be looked upon as simply one of the parallel generator branches.

In Fig. 1, consider the points A, B and its n branches. By Kirchoff's laws:

(*a*) The algebraic sum of the voltage drops along all paths connecting the same 2 points are equal.

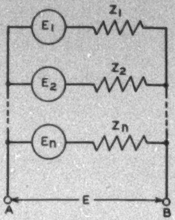


Fig. 1

(*b*) Every impedance Z through which a current I passes exerts an equivalent back-voltage E equal in value to IZ.

(*c*) The algebraic sum of the currents at any point is zero.

From the diagram, and by (*a*), (*b*)

$$E_S - I_S Z_S = E \geq 0; \; S = 1, 2, \ldots, n \qquad (1)$$

Let the currents I_S have 2 components. Then

$$I_S = I_{S0} - I_{S1}; \; S = 1, 2, \ldots, n \qquad (2)$$

Substituting eq 2 in eq 1, and dividing by $Z_S \neq 0$

$$\left(\frac{E_S}{Z_S} - I_{S0}\right) + I_{S1} = \frac{E}{Z_S} \qquad (3)$$

and hence

$$\sum\left(\frac{E_S}{Z_S} - I_{S0}\right) + \sum I_{S1} = E\sum\frac{1}{Z_S} \qquad (4)$$

By (*c*) and eq 2

$$\Sigma I_{S0} - \Sigma I_{S1} = \Sigma I_S = 0 \qquad (5)$$

Substituting eq 5 in eq 4

$$\sum\left(\frac{E_S}{Z_S} - I_{S0}\right) + \sum I_{S0} = E\sum\frac{1}{Z_S} \qquad (6)$$

As I_{S0} is arbitrary, simplification of eq 6 will result if

$$\sum\left(\frac{E_S}{Z_S} - I_{S0}\right) = 0; \text{ or}$$

$$\frac{E_S}{Z_S} - I_{S0} \equiv 0 \qquad (7)$$

The first of these appears sterile. The second leads to direct physical interpretation, and is that adopted by the authors. From another point of view, eq 6 represents a "mean-value theorem" with 2 mutually cancelling terms arbitrarily added; and when used without them, completely dispenses with the fiction of short-circuit currents.

Very truly yours,
I. H. Barkey (A'29)
(Technical Consultant,
2020 52nd St., Brooklyn, N. Y.)

To the Editor:

The paper "A New Method of Calculating Circuits" by W. B. Kouwenhoven and M. W. Pullen in ELECTRICAL ENGINEERING for November 1933, p. 776–9, describes the application of the so-called "short-circuit current solution" in the determination of the currents and voltages in a network consisting of any number of sources of electromotive force operating in parallel and delivering energy to a load (see Fig. 1). By the use of the fictitious short-circuit current of each generator and a fictitious impedance of the network, it is shown in the paper how to calculate readily the common complex voltage E of the system, the determination of which evidently supplies the key to the solution of all the currents of the network.

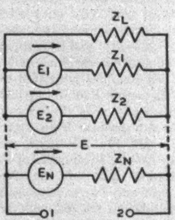


Fig. 1.

The common voltage E across the terminals 1–2 can also be determined by the use of the following obvious alternative form of Thévenin's Theorem (see "Sur un Nouveau Théorème d'Électricité Dynamique," by L. Thévenin, *Comptes Rendus*, v. 97, 1883, p. 159–61): "The voltage between any 2 points in a circuit is equal to the product of the current which would flow through an impedanceless conductor were the latter connected to these 2 points, and the impedance which would exist across these 2 points were all sources of electromotive force removed." The application of this theorem to the circuit shown in Fig. 1 is as follows: The complex current which will flow through an impedanceless conductor connected to terminals 1–2 is evidently

$$\frac{E_1}{Z_1} + \frac{E_2}{Z_2} + \ldots + \frac{E_N}{Z_N},$$

i. e., the sum of the short-circuit current of each generator. The complex impedance between the terminals 1–2 when the voltages E_1, E_2, ..., E_N are removed is

$$\frac{1}{\frac{1}{Z_1} + \frac{1}{Z_2} + \ldots + \frac{1}{Z_N} + \frac{1}{Z_L}}.$$

Therefore

$$E = \frac{\frac{E_1}{Z_1} + \frac{E_2}{Z_2} + \ldots + \frac{E_N}{Z_N}}{\frac{1}{Z_1} + \frac{1}{Z_2} + \ldots + \frac{1}{Z_N} + \frac{1}{Z_L}}.$$

This equation is identical with eq 8 of the paper which is being discussed here.

The foregoing discussion shows that the "short-circuit current" method makes use of the same fictitious short-circuit current of each generator and the same fictitious impedance which are used in a direct application to the circuit under consideration of the alternative form of Thévenin's Theorem given above. It is evident, therefore, that in the treatment of this particular network the use of the "short-circuit current" method is not characterized by advantages superior to those already obtainable by the use of one of the existing artifices of circuit theory. It is probable, however, that the "short-circuit current" method may be advantageously used in solving other types of circuits.

Very truly yours,
MICHAEL J. DI TORO (A'32)
(Electrical Engineer, 1378 West 7th Street, Brooklyn, N. Y.)

To the Editor:

Since the publication of "A New Method of Calculating Circuits" by W. B. Kouwenhoven and M. W. Pullen, in the November 1933 issue of ELECTRICAL ENGINEERING, p. 776–9, the attention of the authors has been called to the fact that the method is also applicable in unbalanced polyphase systems. The treatment for this case is to be found in "Experimental Electrical Engineering," by V. Karapetoff, v. 2, p. 110.

Very truly yours,
W. B. KOUWENHOVEN (A'06, M'22)
(Professor of Electrical Engineering and Assistant Dean, Johns Hopkins University, Baltimore, Md.)

Theory of Probability

To the Editor:

It is to be hoped that the excellent article by Professor Bennett on "Theory of Probability" published in the November 1933 issue of ELECTRICAL ENGINEERING, p. 752–7, will stimulate attempts on the part of engineers to bring the theory into use in a number of fields where it has not yet been generally applied.

That there should be important applications in power system design, to mention one such field, is suggested by the problem of determining the proper number of spare generators, transformers, cables, etc., to insure a satisfactory degree of service reliability. Spare capacity is now too frequently determined by arbitrary rules having little or no logical basis. For example, reserve generating capacity is often taken as a certain percentage of the capacity required for peak load without due regard to the number and size of units. It should almost be self-evident that 6/20,000-kva generating units installed for a peak load of 100,000 kva give less assurance of dependable service than 12 similar units installed for a peak of 200,000 kva, even though in each case the spare capacity is 20 per cent.

To illustrate the fact that as the number of units increases the percentage spare can be materially reduced without sacrificing reliability, the curve, Fig. 1, for generating units has been calculated. To simplify the problem all units are assumed to have the same capacity, and each is assumed to be subject to emergency outage time to the extent of 3 per cent of its service hours. The curve shows the number of spare units required to be running at the time of the peak, plotted against units needed to carry the peak, in order that the probability of load interruption at the time of the peak shall be $\frac{1}{1{,}000}$. For example, it is shown that when one machine is required for load one additional machine, or 100 per cent spare, must be run to insure the desired degree of service reliability. If the system has 5 units for the peak, 2 reserve units or 40 per cent must be run. Twenty units need 4 spares, or 20 per cent. If 2 systems, each having load for 20 units, interconnect to form in effect a 40-unit system, the reserve need be but 6 units instead of 4 each when operating separately. If 5 such systems pool their generating resources the reserve can be reduced to 10 units, or 10 per cent spare, as against 20 per cent before pooling.

The above results are of course based upon hypothetical considerations. Space does not permit more than brief mention of some of the practical considerations that must enter into the solution of an actual problem. For example, account must be taken of the variety of sizes of generating units usually present in an existing system, and of possible short-time overload capacities. It usually will be necessary to calculate probabilities of load outage not only at the time of the peak load but also at loads just under the peak. Again it may be necessary to determine probabilities at times when scheduled turbine, generator, or condenser maintenance temporarily reduces the system capacity, even though at these times the load may be considerably below the peak.

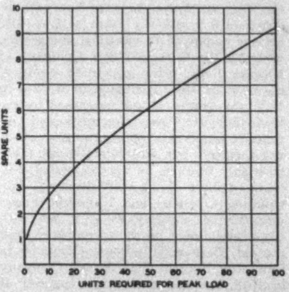


Fig. 1.

A good method of computing probabilities in a problem such as this consists simply of expanding the binomial $(p + q)^n$, where p is the probability that a generating unit will be unavailable (in the case cited $\frac{0.03}{1 + 0.03}$), q the probability that it will be available $\left(\frac{1}{1 + 0.03}\right)$, and n the total number of machines running. The expansion results in $n + 1$ terms, the first of which is the probability that n machines will be simultaneously unavailable, the second the probability that $n - 1$ will be simultaneously unavailable, and so on to the last term which gives the probability that no units will be unavailable. (Compare second paragraph in second column on p. 754 of Professor Bennett's article.) This method presupposes that all available machines are actually running and subject to outage. When certain machines are available but idle and therefore not liable to breakdown the problem is somewhat altered. Other methods are available for dealing with this condition.

Very truly yours,
S. A. SMITH, JR. (A'24, M'31)
80 Park Place, Newark, N. J.

Personal Items

J. Allen Johnson Nominated for Presidency

JOSEPH ALLEN JOHNSON (A'07, F'27) chief electrical engineer of the Buffalo, Niagara and Eastern Power Corporation, Buffalo, N. Y., has been nominated for the presidency of the A.I.E.E. for the 1934–35 term. He was born at Northboro, Mass., June 21, 1882. In 1905 he graduated from the Worcester Polytechnic Institute with the degree of B.S. in E.E. From 1905 to 1912, he was employed in electrical engineering work by the Ontario Power Company of Niagara Falls, being appointed electrical engineer of that company in 1912. In 1917, this company was purchased by the Hydro-Electric Power Commission of Ontario, of which Mr. Johnson became assistant engineer, but still retained his other position. In 1918, he was appointed electrical engineer of the Cliff Electrical Distributing Company and Hydraulic Power Company of Niagara Falls, N. Y., and with the consolidation of these companies and the old Niagara Falls Power Company to form The Niagara Falls Power Company in 1918, he became electrical engineer of the enlarged company. In this capacity he was responsible for many important features of the electrical design of the Niagara developments during the period of their rapid growth from 1918 to 1924. In 1929, he was appointed chief electrical engineer of the Buffalo, Niagara and Eastern Power Corporation, which position he now holds. During his career Mr. Johnson has taken a prominent part in the development of the art of power generation and transmission. Perhaps the most important of such developments was that of the system of generator voltage control by individual regulators, which he originated and pioneered in the plant of the Ontario Power Company about 1910, and which he described in a contribution to the technical press shortly thereafter. His contributions to the art of generator testing by means of the retardation method are also well known. Mr. Johnson has contributed to the Institute several important papers on such subjects as reactors in hydroelectric stations, the retardation method of determining losses in hydroelectric generating units, fire protection in a-c generators, and operating aspects of reactive power. As joint author he has also made contributions on power developments at Niagara Falls, lightning protection for transformers, and fundamentals of design of electric energy delivery systems, the latter to be presented at the coming winter convention. He has served the Institute as a member of the electrochemistry and electrometallurgy, electrical machinery, instruments and measurements, protective devices, and research committees. He became a director of the Institute in 1928, served as chairman of the membership committee for the 2 years 1929–31, and is at present chairman of the national committee on transfers, as well as of a special committee to consider the dues of Associates and related matters. He is also a member of the Edison medal committee and the executive committee, and vice president of the North Eastern District (No. 1). He was organizer and first chairman of the Niagara Frontier Section, and served in that capacity from the date of its organization, February 10, 1925, to July 31, 1926. It is also of interest that he was the first chairman of the Worcester Polytechnic Institute Branch of the A.I.E.E. in 1905. Besides his Institute activities, Mr. Johnson served the former National Electric Light Association as chairman of its electrical apparatus committee, as a member of its power systems engineering committee, and is at present chairman of the electrical equipment committee of the Edison Electric Institute. He is also a member of the American Association for the Advancement of Science, and a member of the Electrical Standards Committee of the American Standards Association.

Vice Presidential Nominees are McMillan, Meyer, Post, Tapscott, and Timbie

FRED ORVILLE MCMILLAN (A'14, M'26, F'33), research professor of electrical engineering, Oregon State College, Corvallis, has been nominated to serve the Institute as vice-president representing the Northwest District (No. 9). He was born at Albia, Iowa, May 12, 1890. In 1912 he received the degree of B.S. in E.E. from Oregon State College and that of M.S. in E.E. from Union College, Schenectady, N. Y., in 1919. In 1912 he entered the student engineering course of the General Electric Company at Schenectady, and was transferred to the engineering department of that company in 1914. He was engaged in experimental and designing engineering work at the Schenectady works until 1920. He was appointed assistant professor of electrical engineering at Oregon State College in 1920, associate professor in 1923, and to his present position of research professor in 1930. He is a registered professional engineer in the state of Oregon, and in addition to academic work has acted as consulting electrical engineer for a number of public utilities, the Port of Portland, Ore., in 1925, and the United States Bureau of Fisheries from 1929 to 1933. Mr. McMillan has served the Institute as counselor for the Oregon State College Branch, 1926–32, and 1933–34; chairman of the Northwest District committee on Student activities, 1927–28; and a member of the national committee on student Branches, 1931–34. He also has presented a number of technical papers and discussions before the Institute, several of these having to do with radio interference from high voltage insulators. Mr. McMillan is a member of the Society for the Promotion of Engineering Education and of the Northwest Electric Light and Power Association. He also is a member of the following scholastic honor societies: Phi Kappa Phi, Sigma Xi, Tau Beta Pi, Eta Kappa Nu, and Sigma Tau.

FRANK J. MEYER (A'13, M'17) vice-president in charge of operation for the Oklahoma Gas and Electric Company, Oklahoma City, has been nominated to serve the Institute as vice-president representing the Southwest District (No. 7). He was born in Grant City, Mo., July 12, 1884. In 1891 he moved with his parents to Oklahoma territory where his father, a Presbyterian minister, did missionary work among the Creek and Seminole Indians. Between 1901 and 1904, he was meter man for the Oklahoma Gas and Electric Company, and between 1904 and 1906 attended Pratt Institute, Brooklyn, N. Y., where he graduated with the 1906 class in applied electricity. Following graduation, he spent 18 months in Porto Rico as assistant electrician for the Guanica Centrale Sugar Company. He returned to Oklahoma in the fall of 1907 and entered the services of the Oklahoma Gas and Electric Company at Oklahoma City, as chief electrician. In 1920 he was made general superintendent of the company and in 1924 became assistant to general manager in charge of operations. In May 1931 he was appointed to his present position of vice-president in charge of operation for the Oklahoma Gas and Electric Company, a subsidiary of the Standard Gas and Electric Company. Mr. Meyer has been quite active in A.I.E.E. work in the Southwest.

GEORGE GILBERT POST (A'11, F'33) vice-president in charge of power for The Milwaukee Electric Railway and Light Company, Milwaukee, Wis., and also vice-president and director of the Wisconsin Electric Power Company, has been nominated to serve the Institute as vice-president representing the Great Lakes District (No. 5). He was born near Madison, Wis., in 1881. In 1904 he graduated from the

University of Wisconsin, Madison, with the degree of B.S. in E.E. The 2 years following graduation were spent as an inspector in the electrical engineering laboratory of the University of Wisconsin. In June 1906 he entered the service of The Milwaukee Electric Railway and Light Company as an assistant in the lighting department where he worked as draftsman, material clerk, and statistician; in 1909 he became superintendent of electrical testing for this company, and in 1910 became electrical engineer of the lighting department. When there was a change of management in 1911, he was made head of the electric distribution department, and held this position until late in 1929 when he was appointed to his present position as vice-president in charge of power. Mr. Post has served the Institute as a member of the committee on power transmission and distribution 1922–26, and the committee on power generation 1932–34. He also has been active on technical committees of the Association of Edison Illuminating Companies, and the Edison Electric Institute. For the former National Electric Light Association, he was chairman of the underground systems committee 1922–23, and vice-chairman of the engineering national section 1932. He also has been active in local engineering circles in Milwaukee and Wisconsin, and is a director of the Milwaukee Engineers' Society.

Ralph Henry Tapscott (A'18, F'29) vice-president of the New York Edison Company and of the United Electric Light and Power Company, New York, N. Y., has been nominated to serve the Institute as vice-president representing the New York City District (No. 3). He was born in Brooklyn, N. Y., August 31, 1885. In 1909 he graduated from Union College, Schenectady, N. Y., with the degree of B.S. in E.E. He then joined the testing department of the General Electric Company at Schenectady, transferring shortly afterward to the lighting engineering department where his duties largely involved work with the New York group of utilities. In 1917 Mr. Tapscott became assistant chief electrical engineer of the New York Edison Company, and in 1925 was made electrical engineer of that company. In 1932 he was appointed to his present positions as vice-president of the New York Edison Company and of the United Electric Light and Power Company. Mr. Tapscott has served the Institute as a member of the standards, electrical machinery, power transmission and distribution, headquarters, Edison medal, and finance committees, and the board of examiners. He also has served the New York Section as secretary and as chairman. In 1930 he was elected a director of the Institute for the term expiring July 31, 1934. Among other societies, he has been chairman of the electrical apparatus committee of the former National Electric Light Association, and later a member of its engineering national committee. At present he is chairman of the light and power group of representatives on the Electrical Standards Committee of the American Standards Association. He also is a vice-president of the General Electric Test Alumni Association.

William Henry Timbie (A'10, M'12, F'24) professor of electrical engineering and industrial practice at Massachusetts Institute of Technology, Cambridge, has been nominated to serve the Institute as vice-president representing the North Eastern District (No. 1). He was born at Pittsfield, Mass., August 20, 1877. In 1901 he graduated from Williams College with the degree of bachelor of arts. From 1901 to 1902 he taught at Westerleigh Collegiate Institute, New Brighton, L. I., N. Y. Between 1902 and 1911 he was instructor of industrial electricity at Pratt Institute, Brooklyn, N. Y., spending the summers from 1904 to 1907 as tester in the works of the General Electric Company, Pittsfield, Mass. From 1911 to 1918 he was head of the department of applied science at Wentworth Institute, Boston, Mass., and from 1918 to 1919 was editor-in-chief of the committee on education and special training of the U. S. War Department. He has been at M. I. T. since 1919, his principal duties being the organizing and conducting of the course in coöperative electrical engineering. Professor Timbie is the author of the following books: "Elements of Electricity," 1910; "Essentials of Electricity" 1913; "Alternating Current Electricity" (*with H. H. Higbie*) 1914; "Essentials of Alternating Currents" (*with H. H. Higbie*) 1919; "Principles of Electrical Engineering" (*with V. Bush*) 1922; "Industrial Electricity" 1924. In 1925 he contributed a paper to the Institute on "The Cooperative Method of Education." He has served the Institute as a member of the Section committee 1929–34, committee on Student Branches 1925–28 and 1929–34, having been chairman of this committee 1929–33. He also has served as a member of the committee on education 1929–33, and committee on general power applications 1924–30. He has been a member of the executive committee of the Institute's Boston Section for many years and at present is chairman of this Section. He has for many years also been counselor of the Student Branch at M. I. T., and for one year was chairman of the Branch counselors committee of District No. 1. He is a member of the following national honorary fraternities: Phi Beta Kappa (scholastic), and Pi Gamma Mu (social science). He also is a member of Kappa Eta Kappa, national social fraternity, and of the Williams Club, New York, N. Y., and Albemarle Club, Boston, Mass.

Farmer, Funk, and Gear Nominated for Institute Directorships

Frank Malcolm Farmer (A'02, M'12, F'13) vice-president and chief engineer of the Electrical Testing Laboratories, New York, N. Y., has been nominated to serve the Institute as a member of its board of directors. He was born in Ilion, N. Y., March 28, 1877. In 1899 he graduated from Cornell University, Ithaca, N. Y., and has since been identified with inspection and testing activities in the electrical field. Following about one year in the test department of the General Electric Company of Schenectady, N. Y., and about $2^1/_2$ years in the inspection division of the U. S. Navy, Brooklyn Navy Yard, he joined the staff of Electrical Testing Laboratories (then the Lamp Testing Bureau) in 1903. In 1906 he was given the title of "engineer" and in 1912 became chief engineer. He has had an extensive experience in research, testing, and inspection in connection with electrical engineering materials and apparatus. Subjects to which he has given special attention are electrical measurements, electrical insulating materials, and electric power cables. He has been active on committees of technical societies dealing with these subjects, has contributed numerous papers to the technical literature, and is the author of "Electrical Measurments in Practice," an associate editor of the "American Civil Engineers Handbook," an author of the "Standard Handbook for Electrical Engineers," etc. He has been interested in welding matters since his association with the research work of the welding committee of the Emergency Fleet Corporation of the World War days. Mr. Farmer has served the Institute as a member of the board of examiners 1923–28, and has been a member of the following committees: standards 1919–22 and 1923–34; technical program 1933–34; award of Institute prizes 1933–34; electric welding 1927–28 and 1930–31; power transmission and distribution 1920–34; and research 1929–34. He was chairman of the research committee 1933–34. Mr. Farmer is a fellow of the American Association for the Advancement of Science, a member of the American Society for Testing Materials (past-president), American Welding Society (past-president), Institution of Electrical Engineers (British), The American Society of Mechanical Engineers, and other engineering organizations. For the American Standards Association he is vice-chairman of the standards council, and chairman of its board of examination, the sectional committee on insulated wires and cables, and the sectional committee on electric welding apparatus.

Nevin Elwell Funk (A'07, M'13) vice-president in charge of engineering of the Philadelphia Electric Company, Philadelphia, Pa., has been nominated to serve the Institute as a member of its board of directors. He was born in Bloomsburg, Pa., November 4, 1883. In 1905 he received the degree of electrical engineer from Lehigh University, Bethlehem, Pa. Mr. Funk served as an apprentice in the Westinghouse Electric and Manufacturing Company, E. Pittsburgh, Pa., in 1905 and 1906. He then worked as subforeman in the employ of the New York Central Railroad Company, Berwick, Pa., during part of 1906, and from 1906 to 1907, served as associate professor of electrical machine design and mathematics at the Georgia School of Technology, Atlanta, Ga. From 1912 to 1913, he was in the employ of the Sterling Switch Board Company in Camden, N. J. From 1907 to 1912, and from 1914 to the present time Mr. Funk has been with the Philadelphia Electric Company occupying the following posts: foreman, station electric construction department; assistant superintendent of Schuylkill station; combustion engineer, Schuylkill No. 1 and No. 2 stations; assistant operating engineer; operating engineer; assistant chief engineer; chief engineer; assistant general manager; and finally, vice-president in charge of engineering. Mr. Funk is also vice-president of the Conowingo Power Company, the Electric Realty Corporation, Philadelphia Electric Power Company, Southern Pennsylvania Power Company, The Susquehanna Electric Company, The Susquehanna Power Company, and The Susquehanna Utilities Company; he is vice-president and director of the Deepwater Light and Power Company, Philadelphia Hydro-Electric Company, and the Philadelphia Steam Company. Mr. Funk is the author of many technical papers. He has served the Institute as a member of the committee on power generation 1924–33. For the Association of Edison Illuminating Companies, he is chairman of the committee on power generation and is a member of the power generation committee of the Edison Electric Institute. He also is a member of The American Society of Mechanical Engineers, the Franklin Institute, the United States Chamber of Commerce, the Philadelphia Chamber of Commerce, the Philadelphia Board of Trade, and the American Committee of the World Power Conference. Mr. Funk is president of the Engineers' Club of Philadelphia, and is a member of the University Club, Lehigh University Club, the Penn Athletic Club, the Philadelphia Country Club, and the Union League, all of Philadelphia.

Harry Barnes Gear (A'01, M'13, F'20) assistant to the vice-president in charge of engineering, construction, and operation of the Commonwealth Edison Company, Chicago, Ill., has been nominated to serve the Institute as a member of its board of directors. He was born in Marietta, Ohio, March 6, 1872. In 1892 he graduated from Marietta College with the degree of bachelor of arts, in 1895 received the degree of M.E. in E.E. from Cornell University, Ithaca, N. Y. Mr. Gear entered the service of the Chicago Edison Company, predecessor of the Commonwealth Edison Company, in 1895. Among the earlier tasks assigned him was the merging of the distribution plants of 4 utility systems, erected in a competitive race for the World's Fair business of 1893, and embodying an assorted lot of voltages, frequencies, and systems. These were merged into the first 2,300/4,000-volt 4-wire 3-phase distribution system to be used in any large city in the United States; it went into service in 1899. In 1911, Mr. Gear was appointed engineer of distribution of the Commonwealth Edison Company, serving in this capacity until 1921. While in this position he was in charge of the design of the power transmission and distribution system of the company. In 1921 he was appointed to his present position, in which his attention has been given to the wide range of problems arising from the conducting of a great utility system in a period of unprecedented growth. While engineer of distribution for the company, Mr. Gear gathered data for a paper on "Diversity Factors" which appeared in the A.I.E.E. Transactions in 1910; this is believed to be the first paper presented before any engineering body on this important subject. During the same year he published jointly with P. F. Williams "Electric Central Station Distribution Systems," a pioneer treatment of this subject and now in its third edition. Papers on various phases of electrical distribution have been presented by him at other times before the Institute. He was a member of the group which met with the representatives of the U. S. Bureau of Standards in 1915 to formulate the first edition of the National Electric Safety Code. For 33 years the incandescent lamp service to retail customers of the company in Chicago has been under his supervision, and he is a member of the lamp subcommittee of the Association of Edison Illuminating Companies. For the Institute, Mr. Gear has been a member of the following committees, safety codes 1914–34 (chairman 1921–24), standards 1923–27, Lamme medal 1932–35, technical program 1932–34, and Edison medal 1932–34. He also has been representative of the Institute on the electrical committee of the National Fire Protection Association 1921–24, and of the National Fire Waste Council 1923–24. In 1910 he received a Chanute Medal award of the Western Society of Engineers (Chicago). He has been a trustee of the University of Chicago and of the Morgan Park Military Academy since 1924, and is a member of the American Association for the Advancement of Science and the Chicago Art Institute. He also is a member of the Union League and South Shore Country Clubs, Chicago.

W. I. Slichter Renominated as Institute Treasurer

Walter Irvine Slichter (A'00, M'03, F'12) professor of electrical engineering at Columbia University, New York, N. Y., has been nominated to succeed himself as treasurer of the Institute. He was born at St. Paul, Minn., May 7, 1873, and graduated from Columbia University, in 1896, with the degree of electrical engineer. Since 1914 Professor Slichter has been an active member of 18 Institute committees and has represented the Institute on 6 joint bodies; he is now a member of 7 committees and a representative on 5 bodies. A full biographical outline of Professor Slichter's career was published on p. 56 of Electrical Engineering for January 1931.

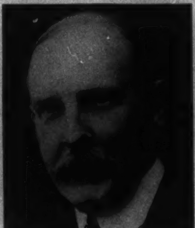
A. E. Kennelly to Receive Edison Medal

Arthur Edwin Kennelly (A'88, M'99, F'13, HM'33, life member and past-president) professor emeritus of electrical engineering, Harvard University and the Massachusetts Institute of Technology, Cambridge, has been awarded the A.I.E.E. Edison Medal for 1933 "for meritorious achievements in electrical science, electrical engineering, and the electrical arts exemplified by his contribution to the theory of electrical transmission and to the development of international electrical standards." Actual presentation of the medal will take place during the forthcoming A.I.E.E. winter convention to be held in New York, N. Y., January 23–26, 1934.

The Edison Medal was founded by associates and friends of Thomas A. Edison, and is awarded annually for "meritorious achievement in electrical science, electrical engineering, or the electrical arts" by a committee consisting of 24 members of the Institute.

Since its establishment in 1904, the medal has been awarded to the following eminent engineers and scientists: Elihu Thomson, Frank J. Sprague, George Westinghouse, William Stanley, Charles F. Brush, Alexander Graham Bell, Nikola Tesla, John J. Carty, Benjamin G. Lamme, W. L. R. Emmet, Michael I. Pupin, Cummings C. Chesney, Robert A. Millikan, John W. Lieb, John White Howell, Harris J. Ryan, William D. Coolidge, Frank B. Jewett, Charles F. Scott, Frank Conrad, Edwin W. Rice, Jr., and Bancroft Gherardi.

In connection with Doctor Kennelly's election as an Honorary Member of the Institute, the highest grade of membership available, a detailed biographical sketch of his career was given in Electrical Engineering for July 1933, p. 512. His marked scientific ability, great versatility in the application of complex theory to practical purposes, continuous contributions to the development of definitions and standards in electrical engineering, and his charming personality has given him an outstanding international reputation.



A. E. KENNELLY

Frank Conrad (A'02) assistant chief engineer of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has been awarded the John Scott Medal by the city of Philadelphia, Pa. This medal, of bronze, was awarded for scientific achievements. It was established in 1816 by John Scott, a chemist of Edinburgh, Scotland, who bequeathed a sum of money to the city of Philadelphia for the maintenance of these awards. Since that time one or more awards have been made annually. Doctor Conrad was awarded the 1930 Edison Medal of the A.I.E.E. "for his contribution to radio broadcasting and short wave radio transmission," as announced in Electrical Engineering for January 1931, p. 60–1, and March 1931, p. 216–8.

H. A. Johnson (M'17) general manager for the receivers of the Chicago (Ill.) Rapid Transit Company, has been appointed director of research of the American Railway Association with the title of chairman. Mr. Johnson has been in charge of extensive testing and research work on air brakes conducted by the Steam Railroad Association. He will head a new committee of the mechanical division which will be devoted to investigations and reports on research problems that may require attention in the opinion of the division.

C. W. Koiner (A'04, F'12) district manager, Southern California Edison Company, Ltd., Redondo Beach, Calif., has been appointed city manager of Pasadena, Calif. Mr. Koiner previously served the city in that same capacity from 1921 to 1925, and for many years prior to that was manager of the municipal light and power department of Pasadena.

Lazare Gelin (A'28), formerly connected with Schneider-Westinghouse in France, has been appointed manager of the foreign division of Kellogg and Tree, an industrial sales promotion company located at New York, N. Y. This firm is engaged in creating a coördinated marketing organization throughout the United States and the leading foreign countries.

H. A. Martin (A'20, M'26) formerly chief engineer of the Peoples Light and Power Company, New York, N. Y., has been appointed division manager of the West Coast Power Company with headquarters in Portland, Ore. He is in charge of the Washington and Oregon properties of the company.

Bryant White (M'20) manager of the electric department of the Delaware Electric Power Company, Wilmington, was recently appointed president of the Kentucky Utilities Company. Mr. White has been an executive of the American Gas and Electric Company since 1920.

J. P. Barton (A'30) has recently been appointed sales engineer in the electrical sheet division of the Empire Sheet and Tin Plate Company, Mansfield, Ohio. Mr. Barton previously was section engineer for the General Motors Radio Corp., Dayton, Ohio.

H. W. Hitchcock (A'15, F'27) chief engineer, Southern California Telephone Company, Los Angeles, has been elected second vice-president of the Engineers' Club of Los Angeles for the year 1933–34.

E. R. Stauffacher (A'15, M'26) electrical protection engineer, Southern California Edison Company, Los Angeles, has been elected secretary of the Engineers' Club of Los Angeles for the year 1933–34.

W. R. Clifford (A'29) chief engineer, Layne and Bowler Pump Corporation, Los Angeles, Calif., has been elected treasurer of the Engineers' Club of Los Angeles for the year 1933–34.

H. V. Schreiber (A'03, M'13) Capital Traction Company, Washington, D. C., has been elected secretary of the electric railway section of the National Safety Council.

Obituary

Calvert Townley (A'01, M'07, F'12, and past-president) a former vice-president of the Westinghouse Electric and Manufacturing Company, died November 27, 1933, at New York, N. Y. He was born October 18, 1864, at Cincinnati, Ohio. In 1886 he graduated from the Sheffield Scientific School of Yale University with the degree of bachelor of philosophy, receiving the degree of M.E. in 1888. In 1887 he was with the Brush Electric Light Company in Cincinnati. Between 1887 and 1904 he spent the first of 2 periods with the Westinghouse Electric and Manufacturing Company. He was erecting engineer for the company in 1887, and for the following year was in charge of the design of electric lighting distribution systems. From 1888 to 1895 he was engaged in commercial and executive work for the Westinghouse company in various capacities. From 1895 to 1897 and from 1898 to 1900 he was manager of the Boston, Mass., office of the company. From 1901 to 1904 he was general agent for the Westinghouse company with headquarters in New York, N. Y., in charge of relations with large transportation interests there. In 1904, he became acting fourth vice-president of the New York, New Haven, and Hartford Railroad Company in charge of all electrical work of that system whether transportation, transmission, lighting, or power. At this time he also was assistant to the president of the Consolidated Railway Company in charge of the engineering, construction, and operation of that company's electrical division. In 1905 he became first vice-president of the Consolidated Railway Company and consulting engineer for the N. Y., N. H. & H. Railroad Company on their electrical work. During this period he also was in charge of the electrical engineering of transportation, power, and lighting systems in a number of cities. During this period he was vice-president of the Connecticut Company and about 30 subsidiaries, in charge of trolley, light, gas, and water companies owned by the New Haven railroad. In 1911 he returned to the Westinghouse company as vice-president and assistant to the president, with headquarters in New York. He held these positions until his retirement in 1931. He was also vice-president of the Westinghouse Electric International Company, trustee of the Westinghouse Company, and director in the Westinghouse X Ray Company, and the Regina Corporation. He was president and director of the Servap Company. During the War he superintended the erection of a turbine factory near Philadelphia, the output being very largely used for the federal government merchant and naval vessel. Mr. Townley served the Institute as a member of the following committees: Edison Medal 1918–23, executive 1919–22, and public policy 1914–19, 1921–22, 1923–24. At the time of his death he was a member of the Coördination Committee of Engineering Societies. He had been a member of the Pan-American engineering committee, the John Fritz Medal board of award, and the American Engineering Council, of which he had served as chairman of the organizing conference. He had served as vice-president and trustee of the United Engineering Trustees, Inc., and on the board of The Engineering Foundation. He was a delegate and member of the executive committee of the engineering delegation to the World Power Conference in London in 1924, and a member of the American Industrial Mission to Mexico that same year. He was elected manager of the Institute in 1905, vice-president in 1908 and president in 1919. He has contributed many papers to technical societies, mostly dealing with power and traction problems. He was a former president of the Yale Engineering Association and a member of the following clubs: Engineers, Yale, Railroad, Bankers (all of New York), New Haven Country, Graduate (New Haven) and Cragston Yacht and Country.

Kempster Blanchard Miller (A'98, M'07, F'27) consulting engineer, Pasadena, Calif., died November 22, 1933. He was born August 14, 1870, at Boston, Mass. In 1893 he graduated from Cornell University, Ithaca, N. Y., with the degree of mechanical engineer. He then entered the U. S. patent office as assistant examiner and was given charge of inventions relating to telephony, continuing at this work until 1896. He then entered the employ of the Westinghouse Electric and Manufacturing Company at East Pittsburgh, Pa. A few months later he became chief electrician of the Western Telephone Construction Company, Chicago, Ill., his particular duties being the designing and superintending of the manufacture of telephone apparatus. In 1898 he engaged in writing text books on telephony and telegraphy and doing other editorial work for the International Correspondence Schools at Scranton, Pa. In 1899 he became electrical engineer of the Kellogg Switchboard and Supply Company in Chicago, Ill., and shortly thereafter took charge of the experimental shop and laboratory of this company. At a somewhat later date he took complete charge of the entire manufacturing plant. During this period he was actively engaged in engineering work on design of new apparatus and systems and made a number of inventions which went into wide commercial use. In 1904 he began practice as a consulting engineer in partnership with S. G. McMeen. He continued in this position until 1919, when he became general manager for the North Electric Manufacturing Company, developing and making machine switching telephone exchange equipments. Since 1922 he has been consulting engineer, specializing in telephony. In connection with his work on telephone systems, he has served as arbitrator and expert witness in telephone litigation. In addition to his telephone work he has designed and constructed hydroelectric plants in Oregon and southern California. He had served as director and general manager in several manufacturing companies and public utility companies. He was the author of "American Telephone Practice," a work of about 900 pages published in 1904, and considered a standard treatise on telephony. He also was the author of numerous technical papers. He had served the Institute as a member of the safety codes committee 1914–15, and committee on telegraphy and telephony 1914–19. He was for some years chairman of the Institute's Chicago Section. He was a past first vice-president of the Western Society of Engineers (Chicago).

John Franklin Stevens (A'94, M'01, F'13, member for life and past vice-president) consulting engineer, Philadelphia, Pa., died December 11, 1933. He was born in Philadelphia, Pa., in 1870. In 1890 he graduated from the University of Pennsylvania with the degree of bachelor of arts, and in 1891 received the degree of M.E. from the same institution on the completion of graduate work in mechanical and electrical engineering. From 1891 to 1893 he was mechanical and electrical engineer for the firm of John F. Stevens and Sons of Philadelphia, manufacturers of industrial iron and steel. From 1893 and 1895 he was in charge of accounting and factory production for the LaRoche Electric Works, serving as secretary and treasurer. In 1894 he undertook the manufacture of measuring instruments as a partner in the Keystone Electrical Instrument Company, becoming owner, designer, chief engineer, and general executive of this firm. He maintained this connection until 1911. Concurrently he was vice-president and consulting engineer for the American Electric Heater Company from 1898 to 1900, and from 1902 to 1913 was general executive and member of the firm in charge of finances for Steward and Stevens Iron Works. In 1911 he entered upon his practice as a consulting engineer. During the War he was vice-chairman of the conservation board and district chairman for southeastern Pennsylvania of the power and conservation division of the Federal Fuel Administration. He was a frequent lecturer and contributor to engineering publications, and was the holder of 6 patents on electrical measuring instruments. He served the Institute as manager 1912–13, and vice-president 1915–17. He also was a member of the following A.I.E.E. committees: Edison Medal 1913–18, executive 1915–17, finance 1913–17 (chairman 1913–17), headquarters 1916–17, membership 1918–19, sections 1912–14, and standards 1911–13. He was a former president of the Engineers' Club of Philadelphia and was a member of the American Electrochemical Society. He was also a member of the Engineers' Club of New York, and the Union League and University Clubs of Philadelphia.

T. Herbert Clegg (A'16, M'21) an electrical engineer for the Tennessee Valley Authority, Knoxville, Tenn., and an assistant to Llewellyn Evans, electrical engineer in charge of operations at Muscle Shoals, died November 20, 1933. He was born at Primos, Delaware County, Pa., in 1887. In 1909 he completed the course in surveying at Temple University, Philadelphia, and in 1911 completed the course in hydraulic engineering conducted by the Scranton Correspondence School. In 1914 he completed the evening course in electrical engineering at Drexel Institute of Philadelphia. In 1906 he served as a switchboard operator for the Philadelphia Rapid Transit Company. From 1910 to 1917 he was engineering assistant to the assistant electrical engineer of the Philadelphia Rapid Transit Company, being engaged on analysis of power plant statistics and economics and assisting in the supervision of power system operation. In 1918 he became superintendent of a steam generating plant of the Atlantic Refining Company of Philadelphia, later in the same year becoming superintendent of power for the Northern Virginia Power Company, Winchester, Va. In 1919 he became assistant to O. M. Rau, power specialist, engaged on investigation work in connection with power plants. He later became special engineer for the Philadelphia Rapid Transit Company and the International Railway Company (Buffalo, N. Y.), retaining these positions for several years. Mr. Clegg was a member of The American Society of Mechanical Engineers, the American Electric Railway Association, and the former National Electric Light Association. He has served the Engineers' Club of Philadelphia as director and as chairman of the finance committee.

Thorburn Reid (A'90, M'98 and member for life) a retired consulting electrical engineer, died November 10, 1933. He was born May 1, 1864, at London, England. He was a graduate of Hampden-Sydney College, Va., and studied at the University of Virginia and Stevens Institute. During his early career he was for a while professor of mechanical engineering at South Carolina State University. He was then in the testing department of the United States Electric Manufacturing Company, Newark, N. J., and was assistant in the laboratory of William Stanley, Jr., for a few months. After a few months as consulting electrical engineer in New York, N. Y., he spent one year with the Edison General Electric Company at Schenectady. He then spent 6 years with the General Electric Company at Lynn, Mass., and in Schenectady, followed by several months with the British Thomson Houston Company in London, England. In 1897 he undertook private practice as a consulting electrical engineer in New York and was active in this capacity for many years until his retirement.

Veator David Mendenhall (A'31) designing engineer, General Electric Company, Philadelphia, Pa., died October 31, 1933. He was born at Yadkin College, N. C., in 1892. He studied at Moravian College for 2 years. From 1913 to 1917 he was marine engineer in the U. S. Navy, and for 16 months of this period was in responsible charge of operation of all power equipment of a 10,000-ton vessel. From 1919 to 1922 he was designer for the R. J. Reynolds Tobacco Company, being engaged on the detailed design of automatic machinery. From 1922 to 1924 he was designer for the General Electric Company, engaged on detail design of electrical switching equipment. In 1924 he became designing engineer of the General Electric Company, and being responsible for the design of considerable outdoor switching equipment.

William Fenner Lamme (A'04) who had been representative of electrical machinery manufacturers and who maintained offices at San Francisco, Calif., died September 16, 1933.

Membership

Recommended for Transfer

The board of examiners, at its meeting of December 20, 1933, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Brooks, Josiah A., asst. E.E., N. Y. & Queens Elec. Lt. & Pwr. Co., Flushing, N. Y.
Fleming, Arthur P., director of research and education, Metropolitan Vickers Elec. Co. Ltd., Manchester, England.
Hickernell, Latimer F., chief engr., Anaconda Wire & Cable Co., Hastings-on-Hudson, N. Y.
McCurdy, Ralph G., noise prevention engr., Am. Tel. & Tel. Co., New York.

To Grade of Member

Albert, John C., asst. E.E. in charge of testing labs., Bureau of Pwr. & Lt., Los Angeles, Calif.
Beverage, Harold H., chief research engr., RCA Communications, Inc., New York.
Blume, Louis F., E.E., Gen. Elec. Co., Pittsfield, Mass.
Borden, Douglas C., managing engr., Elec. Constr. Co., Toronto, Ont. Can.
Canfield, Charles E., mech. engr., Gen. Elec. Co., Pittsfield, Mass.
Danner, Ronald F., gen. supt., Okla. Gas & Elec. Co., Oklahoma City, Okla.
Darrow, Leo H., engr. of bldgs. and equip., N. J. Bell Tel. Co., Newark, N. J.
Findley, Paul B., managing editor "Bell Laboratories Record," New York.
Green, Stanley, secy. and chief engr., Duncan Elec. Mfg. Co., Lafayette, Ind.
Hutton, William S., E.E., Canadian Fire Underwriters Association, Toronto, Ont. Can.
Jennings, Earl B., foreign wire relations engr., Southwestern Bell Tel. Co., Oklahoma City, Okla.
Little, John J., gen. mgr., Northern B. C. Pwr. Co., Ltd., Prince Rupert, B. C. Can.
Plumb, Harold J., transmission line supervisor, Consumers Pwr. Co., Jackson, Mich.
Ports, Earl George, chief engr., Federal Telegraph Co., Newark, N. J.
Putnam, Russell C., asst. prof. of E.E., Case Sch. of Ap. Sci., Cleveland, O.
Siskind, Charles S., instructor, Purdue Univ., Lafayette, Ind.
Sultzer, Morton, protection devpmt. serv. engr., Am. Tel. & Tel. Co., New York.
Taylor, Hamilton D., designing engr., Gen. Elec. Co., West Lynn, Mass.
Webb, Earl B., bldg. and equip. engr., Indiana Bell Tel. Co., Indianapolis, Ind.
Wilson, Stanley M., gen. supt. of equip., Western Elec. Co., Kearny, N. J.

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before January 31, 1934, or March 31, 1934, if the applicant resides outside of the United States or Canada.

Armstrong, C. J., Oklahoma Gas & Elec. Co., Drumright, Okla.
Avery, F. (Member), Southern Bell Tel. & Tel. Co., Atlanta, Ga.
Bain, D. S., Michigan Alkali Co., Wyandotte.
Brown, J. J., 253 Jamesville Ave., Syracuse, N. Y.
Brown, P. F., Indiana Bell Tel. Co., Indianapolis.
Burnett, C. E., RCA Radiotron Co., Inc., Harrison, N. J.
Chambers, H. J., Toronto Hydro-Elec. System, Toronto, Ont., Can.

Cropper, R. E., Canadian Nat. Carbon Co. Ltd., Toronto, Ont., Can.
Danielsson, C. E. J., Empresa de Telefonos Ericsson, S. A. Mexico, D. F., Mexico.
Davis, J. M., Indiana Bell Tel. Co., Indianapolis.
Diehl, A. C. V., Brooklyn (N. Y.) Edison Co., Inc.
Durand, A. G. (Member), New York (N. Y.) Edison Co., Inc.
Ericsson, E. R., Empresa de Telefonos Ericsson, S. A. Mexico, D. F., Mexico.
Foster, S. P., c/o Jenson Bowen & Farrell, Ann Arbor, Mich.
Freedman, E. A., 787 Lexington Ave., New York City.
Fries, P., Jr., 374 E. 141 St., New York City.
Hammond, E. M., Bell Telephone Co. of Pa., Phila.
Hooker, T. (Member), Delaware Pwr. & Lt. Co., Wilmington.
Hull, H. N., Municipal Lt. & Pwr. Plant, Columbus, Ind.
Kiefer, J. F., Delaware Pwr. & Lt. Co., Wilmington.
Kleinau, C. S., So. Calif. Tel. Co., Los Angeles.
Kotraschek, L. C., K. & B. Elec. Equip. Co., Inc., New York City.
LeFever, E. A. (Member), Buffalo, Niagara & Eastern Pwr. Corp., Buffalo, N. Y.
Lips, J. G., Louisville Gas & Elec. Co., Louisville, Ky.
Ludwig, A., Western Elec Co., Kearney, N. J.
Marks, A. M., Elec. Dvpmt. Corp., New York City.
McAdam, R. E., 31 Brunswick Ave., Troy, N. Y.
Megeath, S. A., Jr., 110 Seaman Ave., New York City.
Menger, F. B., Gen. Elec. Co., Schenectady, N. Y.
Metzger, L., 581 Columbus Ave., New York City.
Miller, R. F. (Member), Pocono Pines, Pa.
Millermaster, R. A. (Member), Cutler Hammer Inc., Milwaukee, Wis.
Millikan, J. E., 83 N. 20 St., Columbus, Ohio.
Musson, C. E., H. E. Musson & Co., Oklahoma City, Okla.
Pettengill, H. C., 39 E. Westfield Ave., Roselle Park, N. J.
Point, C. L., Virginia Elec. & Pwr. Co., Richmond, Va.
Potter, E. A., Am. Tel. & Tel. Co., New York City.
Prosser, W. H., The Lincoln Elec. Co., Cleveland, Ohio.
Ramsey, W. H., Oscar D. & Herbert V. Dike, New York City.
Ranney, H. W., Buffalo Tech. High School, Buffalo, N. Y.
Settles, O. P., Mountain States Tel. & Tel. Co., Denver, Colo.
School, R. A., Pub. Serv. Co. of Indiana, Connersville.
Shepherd, J. O'D., Southern Bell Tel. & Tel. Co., Atlanta, Ga.
Simpson, C. N. (Member), Gatineau Pwr. Co., Ottawa, Ont., Can.
Stanley, Foster L., Indiana Bell Tel. Co., Indianapolis.
Thomas, E. J., Gen. Elec. Co., Ft. Wayne, Ind.
Thorn, C. S. (Member), Birmingham Elec. Co., Birmingham, Ala.
Thrush, G. H., Jr., Elec. Stor. Batt. Co., Pittsburgh, Pa.
Wallsten, S. E., Empresa de Telefonos Ericsson, S. A. Mexico, D. F., Mexico.
Wantland, J. S., Oklahoma Gas & Elec. Co., Oklahoma City.
Warren, W. J., Univ. of Ill., Urbana.
Wilhelm, H. A., Square D Co., Milwaukee, Wis.

52 Domestic

Foreign

Basu, M., E. Marelli & Co., Milano, Italy.
Bhavnani, K. J., Messrs. Callender's Cable & Constr. Co., Ltd., Bombay, India.
Bongale, R. M., Tata Hydro Elec. Pwr. Supply Co., Ltd., Parel, Bombay, India.
Gates, B. G., The British Electrical & Allied Industries Research Assn., London, Eng.
Ghosh, K. C., E. Marelli & Co., Milano, Italy.
Hayes, W. E. (Member), Luton Corporation Electricity Sta., Luton, Bedfordshire, Eng.
Mill, A., Asea Elec. Ltd., Wellington, New Zealand.
Mortlock, J. R., The British Thomson Houston Co., Ltd., London, Eng.
Preston, G. W. (Member), Copper Devpmt. Assoc., London, S. W. 1, Eng.
Roberts, E. L., Metropolitan-Vickers Elec. Co., Ltd., Manchester, Eng.
Winterbottom, J. G., Lancashire Cotton Corp., Ltd., Manchester, Eng.

11 Foreign

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Black, H. M., 425 South Ave., Wilkinsburg, Pa.
Blackhall, Harold J., Postlagernd, Essen, Germany.
Boicourt, Frank R., Rockwell City, Iowa.
Bugnion, Frank E., 14 Clinton St., Cambridge, Mass.
Code, F. L., 6061 Trafalgar St., Vancouver, B. C., Can.
Dean, George H., Corrie, Old Shoreham Road, Shoreham-by-Sea, Eng.
Ghamat, S. B., School of Engg. of Mil., Milwaukee, Wis.
Hamby, H. M., 708 F St., N.E., Washington, D. C.
Hirsch, Chas. J., Level Club Hotel, 253 W. 73rd St., New York City.
How, John H., 42 Wai Oi Road East, Canton, China.
Kahale, N. A., Box 434, W. Lafayette, Ind.
Lober, Charles, K. C. P. & L. Co., 1330 Baltimore Ave., Kansas City, Mo.
Shifrin, Leonard I., c/o Tanenbaum, 12 Pinehurst Ave., New York City.
Soskin, Samuel B., 1225 S. Calif. Ave., Chicago, Ill.
Strommer, E. N., 7229 Penn Ave., Pittsburgh, Pa.
Talbot, H. L., 55 Pine Ave. E., Montreal, Que., Can.
Weber, George A., 537 Addison Ave., Palo Alto, Calif.

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, during November are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface or text of the book in question.

INDUSTRIAL HEAT TRANSFER. By A. Schack, trans. from the German by H. Goldschmidt and E. P. Partridge. N. Y., John Wiley & Sons, 1933. 371 p., illus., 9x6 in., cloth, $5.00. Supplies simple formulas or graphs which will enable the engineer to deal with problems of furnaces and heat exchangers. Based upon the author's 7-yr. experience as investigator of heat-transfer problems. Converted all equations to English units. A useful bibliography is included.

PROCEDURE HANDBOOK of ARC WELDING DESIGN and PRACTICE. By Lincoln Elec. Co. Cleveland, Ohio, Lincoln Elec. Co., 1933, 434 p., illus., 9x6 in., cloth, $1.50. *Contents:* Welding methods and equipment; technique of welding; procedures, speeds, and costs for welding mild steel; weldability of metals; designing for arc-welded steel construction of machinery; designing for arc-welded structures; and typical applications of arc welding in manufacturing, construction and maintenance.

STAHLHOCHBAUTEN, ihre Theorie, Berechnung und bauliche Gestaltung, vol. 2. By F. Bleich. Berlin, J. Springer, 1933. 934 p., illus., 11x8 in., cloth, 46.50 rm. The 3 main sections of this volume treat of mill buildings, roofs, and masts and towers for electric lines and radio. Fifty pages are given to masts and towers. Gives an excellent view of German practice in the design of steel structures.

STEAM and GAS ENGINEERING. By T. E. Butterfield, B. H. Jennings, and A. W. Luce. 2 ed. N. Y., D. Van Nostrand Co., 1933. 488 p., illus., 9x6 in., cloth, $4.50. An introduction to the development of heat and power from fuels, which emphasizes steam equipment somewhat more than internal-combustion engines. The material is based on thermodynamics, the construction, and operation of a variety of apparatus being used as a background. The new edition has been thoroughly revised.

The UNIVERSE of LIGHT. By Sir William Bragg. N. Y., Macmillan Co., 1933. 283 p., illus., 9x6 in., cloth, $3.50. For the general reader interested in the new physics. Taking as the thread of his story the old rivalry between the corpuscular and wave theories of light, Sir William writes of the early researches in light from which present physical concepts have arisen. The work is a masterly popular account of the evolution of physical science.

VOCATIONAL GUIDANCE IN ENGINEERING LINES. Edit. by Am. Assn. of Engrs.; Editorial Committee—J. A. L. Waddell, *Chairman*, Frank W. Skinner, Harold E. Wessman. Pub. 1933 by Mack Printing Co., Easton, Pa. 521 p., illus., 9x6 in., cloth, $2.50. The aim of this book is stated to be "a simple, practical yardstick by which those young men who aspire to be engineers can measure their natural fitness for the tasks imposed by the profession, their ability to content themselves with its probable rewards, and the intensity of their own desires to join the ranks of the Sons of Martha." Some 60 chapters, each by a well known practitioner in some important branch or specialty of engineering, give an unusually broad picture of the whole field. In addition, such general subjects as engineering ethics, idealism in engineering, vocational guidance, and aptitude tests, are discussed.

HOW to do PUBLICITY. By Raymond C. Mayer. N. Y. and Lond., Harper & Bros., 1933. 258 p., 9x6 in. cloth, $3.00. Discussion of practical methods of conducting publicity including newspaper, magazine, trade paper, radio, etc., as well as publicity found useful by corporations, trade associations, charitable, scientific and professional societies. (A.I.E.E.)

AUTOMOBILE ELECTRICAL EQUIPMENT. By A. P. Young and L. Griffiths. Lond., Iliffe & Sons, Ltd., 1933. 336 p., illus., 9x6 in., cloth, 15s. Covers the electrical equipment used with the internal-combustion engine on land and sea, and in the air. The principal types of British machines are described and illustrated.

BOOK of STAINLESS STEELS, Corrosion Resisting and Heat Resisting Chromium Alloys. Ed. by E. E. Thum. Cleveland, Ohio, Am. Soc. for Steel Treating, 1933. 631 p., illus. 9x6 in., cloth, $5.00. The manufacture, properties, and uses of corrosion and heat resistant chromium alloys are discussed. The properties of the typical alloys are presented, and the requirements of a large number of consuming industries are explained. A useful classified list of trade names is included.

ELECTRICAL CIRCUITS and MACHINERY. Vol. 2, ALTERNATING CURRENTS. By J. H. Morecroft and F. W. Hehre. 3 ed. N. Y., John Wiley & Sons, 1933. 582 p., illus., 9x6 in., cloth, $4.50. A presentation of the fundamental principles of alternating currents, for use in elementary undergraduate courses by any students except those specializing in electrical machinery. In this edition new material has been added and the book thoroughly revised.

ELECTRICAL ENGINEERING PRACTICE, a Practical Treatise for Electrical, Civil and Mechanical Engineers, v. 3. By J. W. Meares and R. E. Neale. 4 ed. Lond., Chapman & Hall, 1933. 920 p., illus., 9x6 in., cloth, 30s. Designed to provide students and engineers with a survey of the whole field of electrical engineering. The 3 volumes cover the generation, distribution, and uses of electricity in a practical way. In volume 3 electrical motors and their control, and the applications of electrical energy in industrial operations and processes, in traction and marine propulsion, and in agriculture are fully described. Specifications, testing and rules and regulations are also considered.

ELEKTRISCHE SCHALTVORGÄNGE und verwandte Störungserscheinungen in Starkstromanlagen. By R. Rüdenberg. 3 ed. Berlin, Julius Springer, 1933. 634 p., illus., 10x7 in., cloth, 42 rm. A detailed presentation of the transient phenomena that occur in electric installations as a result of switching, short circuits, and other break-downs. The third edition is revised and enlarged.

Engineering Societies Library

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MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Industrial Notes

The Louis Allis Co. Appoints Charles F. Norton.—According to a recent announcement, Charles F. Norton, formerly vice-president and general manager of the Howell Electric Motors Co., who recently became associated with The Louis Allis Co. of Milwaukee, has been appointed general sales director of the latter organization.

Canadian Bristol Co. Organized.—The Bristol Company, Waterbury, Conn., announces that in order to serve the Canadian market still better and to expand and consolidate its present Canadian service laboratory of 12 years' standing so as to include sales, service and manufacturing, a separate company, The Bristol Company of Canada, Ltd., has been incorporated. Factory and general headquarters will be located at 64 Princess St., Toronto, Ont., where Bristol recording, indicating and control instruments will be made. J. S. Mayberry, for 10 years with the parent company, has been appointed manager.

New Insulation Tester.—The Sound Engineering Corp., 416 Leavitt St., Chicago, announces a new instrument for testing the dielectric strength of sheet materials, such as paper, rubber, mica, etc. Means are also provided for testing complete units such as transformers, motors, insulated wire, etc. The testing equipment is completely self-contained in an all metal case, measuring 16 by $18^1/_2$ by $8^1/_4$ inches and weighes 65 pounds. Among the features emphasized by the manufacturer are absolute safety to the operator, accuracy, smooth and convenient control of voltage from 200 to 10,000 volts, and definite pressure and even distribution of the electrical field over the test sample. A Weston vane type meter using a 10 milliampere field coil is employed in conjunction with 2 sets of resistors to measure the voltage across the test sample. The meter is calibrated in 3 ranges, 0–1,000, 0–5,000, and 0–10,000 volts. The secondary circuit is so designed that the instant a breakdown in the test sample occurs the voltage indicated on the meter drops to approximately zero, thus providing a direct, accurate means for reading the actual potential at insulation failure.

Westinghouse Reports Central Station Trends in 1933.—In its annual engineering review for 1933 the Westinghouse Electric & Mfg. Co. notes that the 165,000 kw unit for the Richmond Station of the Philadelphia Electric Co. is now under construction, comprising a tandem compound turbine with a single generator of 183,334 kva capacity. In the hydroelectric field the station of the New Kanawha Power Company, consisting of 4 units of 30,000 kva each, was the only one of any importance to be built. During the year the Westinghouse Company received an order for 2 of the Boulder Dam generators each of 82,500 kva.

In the transmission and distribution field, continued progress is reported in the study of lightning phenomena in the laboratory and in field experiments. These studies indicate that apparatus may be designed with proper protective measures to withstand surges actually encountered in service. This, however, involves an increase in cost of the equipment and there is, therefore, an economic limit to how far the improvement can be carried. An example of built-in protection is a surge-proof distribution transformer.

During the year a number of voltage regulators for feeders of the higher voltages were sold, operating on the principle of the tap-changing transformer. These regulators are intended to supplement the line of induction regulators. Considerable advance has been made in high voltage fuses. Deion power fuses of 7,500, 15,000, and 23,000 volts were developed, with interrupting ability of 325,000, 500,000, and 600,000 kva, respectively. In these fuses a tube lined with boric acid provides the source of deionization of the arc stream created by the rupture of the fuse element.

A great improvement has been made in the current type of telemeter, in which a small direct current proportional to the quantity to be measured is transmitted to distant receivers. The earlier forms were inherently sluggish in response due to the necessarily large devices used to modify the value of the transmitted current. These could not be speeded up without introducing hunting.

G-E Progress Review.—Among the developments in the General Electric Company's review of engineering progress during 1933, the modernization of industrial plants is reported as an important factor in the developmental work of the year, and improvements were made in the design, construction, or operating characteristics of practically every class of apparatus for industrial service. A new element was added last year by an increased modernization demand for central-station switching and distribution equipment, stimulated by the rising curve of kilowatt-hour consumption. The modernization in this case included the replacement of windings of transformers to provide higher ratings and improved protection, and the replacement of parts of oil switches by oil-blast mechanisms to increase their rupturing capacity—in some instances as much as 300 per cent.

The maximum rating of waterwheel generators was increased to 82,500 kva for two machines of this type for the Boulder Dam development; previous maximum rating being those of the 77,500 kva units installed at Dnieprostroy, Russia.

Unusual activity prevailed in the development of motors and a new type of variable-speed alternating-current machine, utilizing Thyratron tubes, was built and tested. A supersynchronous motor of record capacity was constructed and additional ratings were provided in machines intended for operation in gaseous atmospheres or other hazardous conditions. A complete redesign of fractional-horsepower motors was effected which established common mounting dimensions for all types of these motors of a given output rating. For many applications, they were provided with ingenious elastic supports to insure quiet operation.

Transformers embodying revolutionary changes in design were made possible by the adoption of Pyranol, the new non-inflammable synthetic insulating and cooling medium for use in place of the conventional transformer oil. A reduction of about one-half was secured in the physical dimensions of these transformers. Pyranol was used also as a treating medium for capacitors, thereby effecting a reduction in volume of about one-third as compared with previous designs.

Research work was continued actively through the year. Lightning investigations were made both in the field and the laboratory to improve the continuity of electric service, and a 2,000,000-volt lightning generator was utilized for the commercial impulse testing of transformers. The chemical and physical characteristics of magnetic sheet steels were improved, and permanent magnet alloys of greatly increased strength were developed which made it possible to obtain new information in regard to the nature of magnetic phenomena.

Trade Literature

Motors.—Catalog 33, 24 pp. Describes Marble-Card motors, generators, motor generator sets and rotary convertors. Marble-Card Electric Co., Gladstone, Mich.

CO$_2$ Meters.—Folder. Describes CO$_2$ recording meters for measuring combustion efficiency. The Brown Instrument Co., Wayne Ave., Philadelphia, Pa.

Pyrometers.—Bulletin. Describes indicating, thermoelectric type pyrometers for panel or wall mounting, portable use, and multiple point installations. Mishawaka Industrial Instrument Mfg. Laboratory, Mishawaka, Ind.

Diesel Generating Sets.—Bulletin 812-A, 4 pp. Describes Buda, full Diesel generating sets ranging in size from 10 to 90 kw. The high speed, light weight Diesel engine is manufactured under a German license. The Buda Co., Harvey, Ill.

Blowers.—Catalog 833, 40 pp. Describes various types of blowers; illustrates applications and includes comprehensive tables giving detailed information. Ilg Electric Ventilating Co., 2850 N. Crawford Ave., Chicago, Ill.

Capacitors.—Bulletin 710, 16 pp. Describes box type and rack type capacitors for power factor correction. Contains complete details of construction as well as dimensions and weights, also tables for determining the proper size capacitor required for correction of low power factor conditions in practically any plant. Ideal Electric & Mfg. Co., Mansfield, O.

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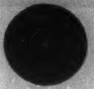

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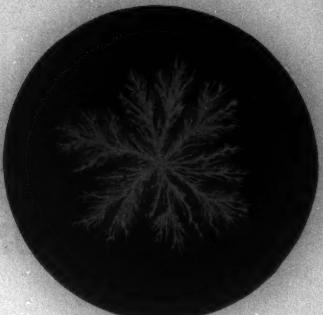

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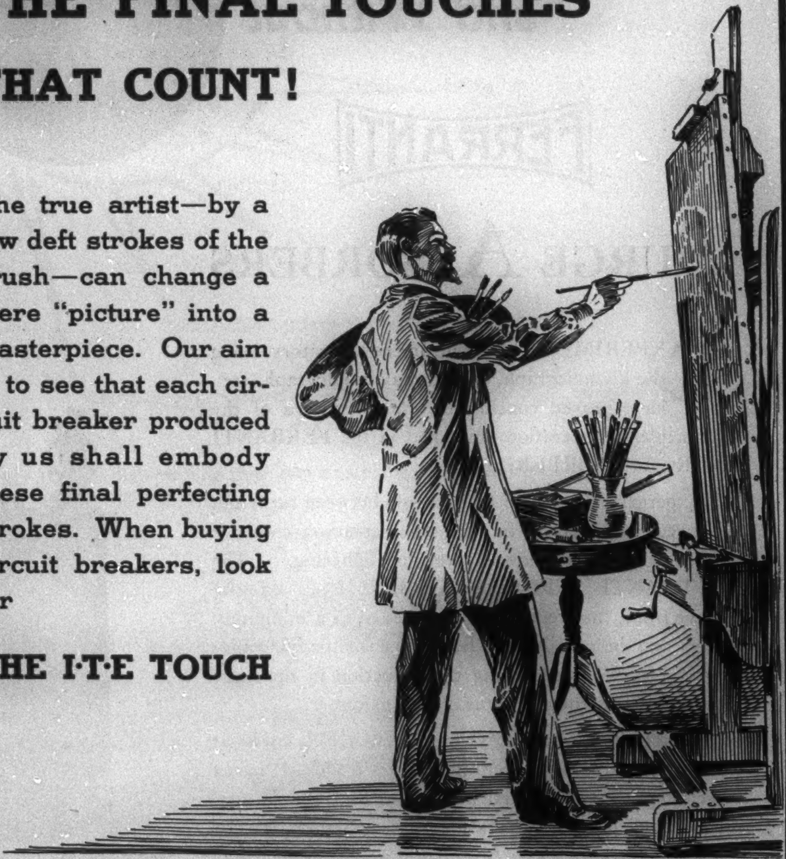

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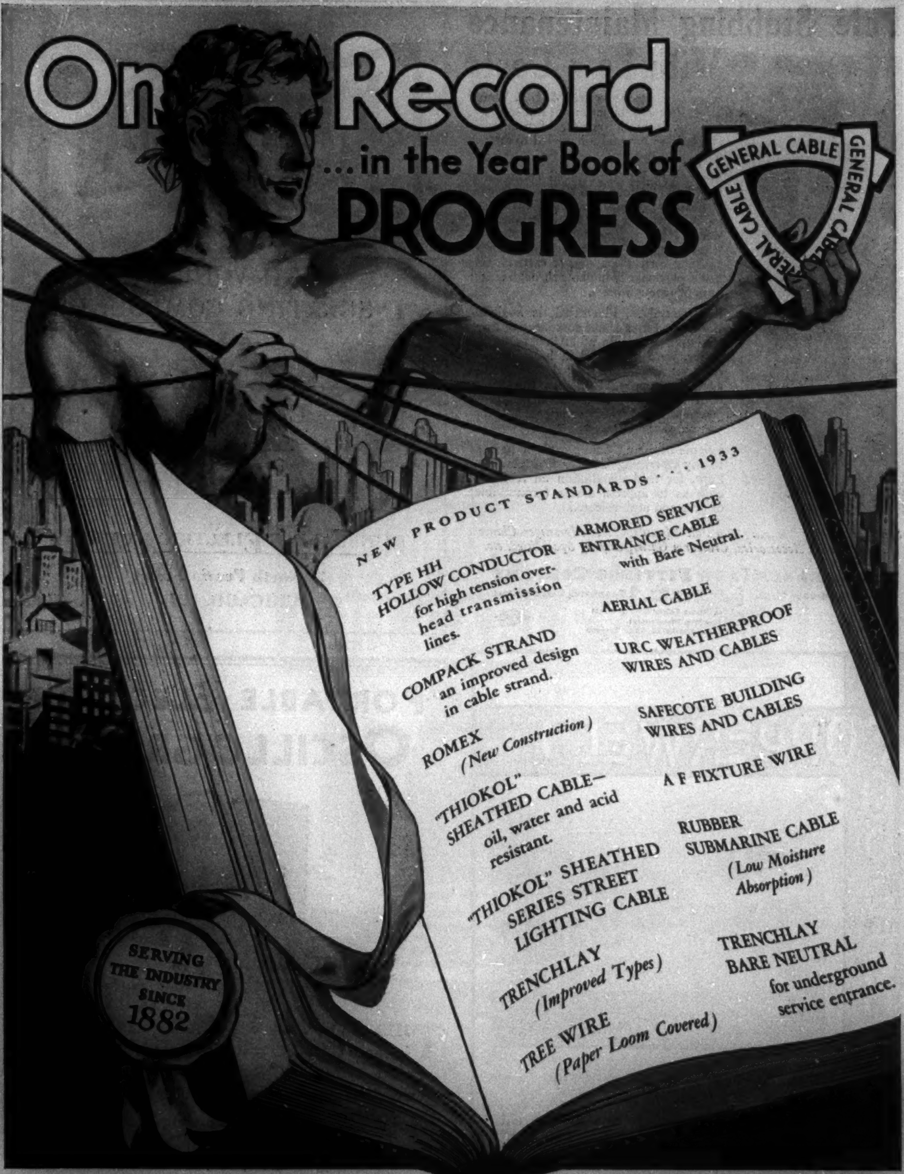
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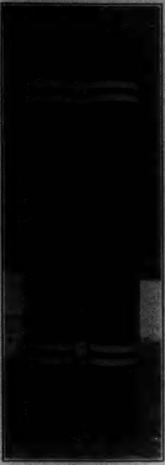

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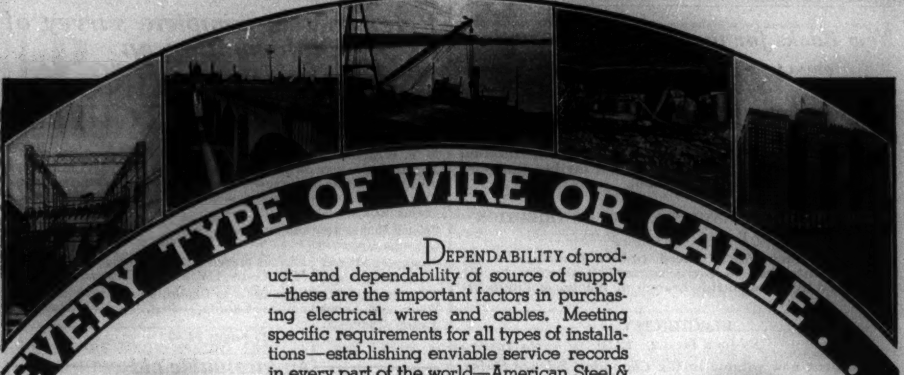

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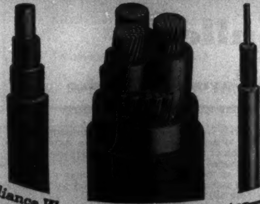

Left—Reliance Weatherproof Wire. Center—Varnished Cambric Cable. Right—Rubber Covered Wire.

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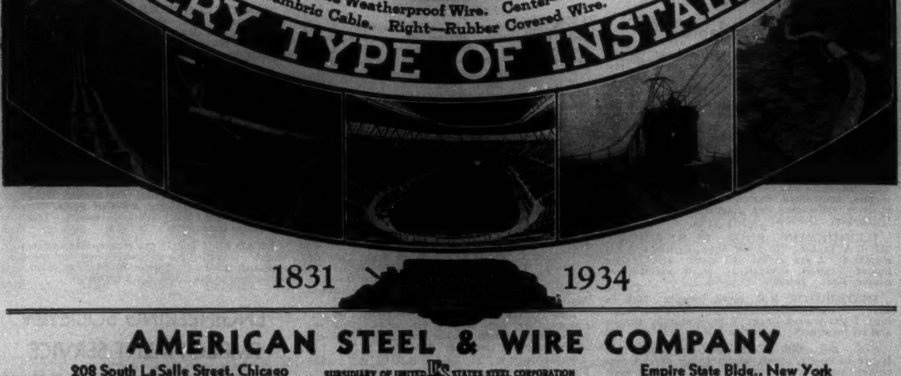

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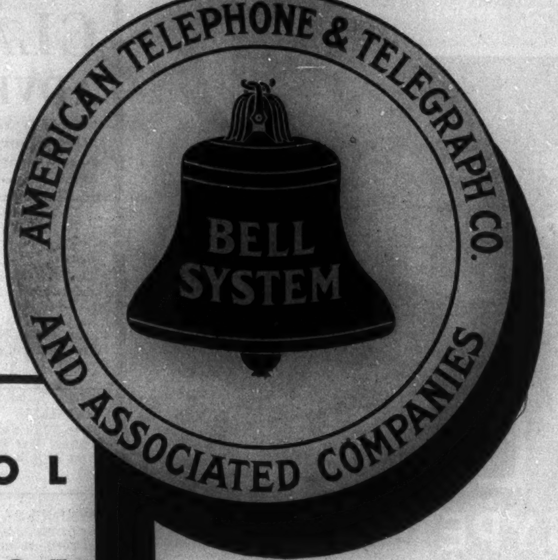

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TYPE VL
TYPE RL
TYPE TL

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